PB84-246347

Technology Assessment of Aquaculture Systems for Municipal Wastewater Treatment

Waste and Water International, Emeryville, CA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Aug 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-246347

EPA-600/2-84-145
August 1984

TECHNOLOGY ASSESSMENT
OF
AQUACULTURE SYSTEMS FOR MUNICIPAL WASTEWATER TREATMENT

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EPA Contract No. 68-03-3016

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-84-145

2.

3. RECIPIENT'S ACCESSION NO.
PB85 246347

4. TITLE AND SUBTITLE
Technology Assessment of Aquaculture Systems for Municipal Wastewater Treatment

5. REPORT DATE
August 1984

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Henry C. Hyde, Roanne S. Ross, and Leslie Sturmer

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Waste and Water International
Emeryville, CA 94608

10. PROGRAM ELEMENT NO.
CAZB1B

11. CONTRACT/GRANT NO.
68-03-3016

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory-Cin., OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Jon H. Bender (513) 684-7620

16. ABSTRACT

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities that use wastewater treatment alternatives to reduce costs or energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in the United States. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Municipal Environmental Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and technical and economic feasibility of using aquaculture systems for municipal wastewater treatment facilities.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT

19. SECURITY CLASS *(This Report)*

20. SECURITY CLASS *(This page)*

21. NO. OF PAGES
133

22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development are the necessary first steps in problem solution, and involve defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drink water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communication link between the researcher and the user community.

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities that use wastewater treatment alternatives to reduce costs or energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in the United States. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Municipal Environmental Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and technical and economic feasibility of using aquaculture systems for municipal wastewater treatment facilities.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

Aquaculture involves the production of aquatic organisms, both flora and fauna, under controlled conditions, primarily for the generation of food, fiber, and fertilizer. The scope of this assessment is limited to aquaculture systems for domestic wastewater treatment. Wastewater aquaculture involves a variety of organisms. Aquatic macrophytes (water tolerant vascular plants), finfish, invertebrates, and integrated systems are the major components considered in this assessment.

Recently, increased attention has been given to the use of designed aquaculture systems for improvement of water quality and wastewater treatment system capacity. Aquaculture systems are being used to achieve secondary and advanced wastewater treatment. Many current systems use aquaculture components for removal of specific pollutants such as biochemical oxygen demand, suspended solids, nutrients, or metals, or are designed as a polishing step after conventional forms of treatment.

Experts in the field recommend that current research and development efforts should be concentrated on aquatic macrophytes. They conclude that aquatic plant systems, particularly water hyacinths, are ready for routine use in municipal wastewater treatment, at least within the geographical areas where such plants grow naturally. Fish, invertebrates, and integrated systems are in the exploratory or developmental stage and, as such, are not ready for routine use.

All aquatic macrophytes have wastewater treatment potential. The greatest emphasis has been placed on the utilization of water hyacinths and, to a lesser extent, duckweeds. Most of the information now available on the performance of aquatic plants in wastewater treatment processes is based upon these two species.

Water hyacinths thrive in an environment where the average air temperature ranges from 4.4 to 35°C (40 to 95°F). Year-round plant growth in the natural environment is therefore restricted to southern Florida and southern Texas. An aquaculture system may also be installed for seasonal use such as for nutrient removal during the spring and summer months. Aquaculture systems may also be covered to provide an artificial environment.

The status of water hyacinths in wastewater treatment has progressively developed during the past few years of research. Water hyacinths have been extensively studied at the laboratory level and tested at the pilot scale level. Continuation of these efforts has produced a number of full-scale experimental and demonstration systems. The research completed on invertebrate, fish and integrated systems is limited and only includes bench and pilot level studies.

Aquaculture wastewater treatment systems consist of one or more shallow basins, ponds, or raceways in which one or several species of aquatic organisms are cultured. The constructed basins and the systems themselves are generally similar in concept to those used in wastewater treatment pond technology.

Aquatic plant system's treatment mechanisms are functions of the existing physical conditions, the biological habitat and the removal of soluble substances from the water by plant uptake. The primary treatment mechanism operative in animal-based aquaculture treatment systems is the control of suspended solids. By stocking and culturing fish and/or invertebrates in wastewater treatment ponds, simple organics, algae and suspended particuates are converted into animal tissue.

Under most conditions, the cost of an aquaculture system is less than or equal to the cost of a conventional system. Conversion of an existing pond system would result in significantly less cost than an equivalent conventional system. Energy demands for an aquaculture system are significantly less than a conventional system by as much as 80 to 90 percent.

Aquaculture systems are usually limited to suburban and rural communities because of the large land area requirements. Theoretically, an aquaculture system can be designed for any capacity, but because the system is land intensive, the cost and availability of land are limiting factors for use in urban settings.

Recommendations for future aquaculture research include optimization of basin design, testing of design criteria, documentation of costs and labor requirements, and the development of alternative plant systems.

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SECTION 1

TECHNOLOGY DESCRIPTION

INTRODUCTION

Aquaculture involves the production of aquatic organisms, both flora and fauna, under controlled conditions, primarily for the generation of food, fiber, and fertilizer. A review of the developmental history and current worldwide practices in aquaculture production systems has been provided by Bardach et al. (Reference 1). Aquatic biological systems are employed in a variety of wastewater treatment processes, such as activated sludge, trickling filters and lagoons. The use of aquacultural concepts employing higher aquatic plants and animals for the treatment and reuse of municipal wastewaters is now encouraged by federal legislation under the provisions of the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) and the Clean Water Act of 1977 (PL 95-217). Wastewater aquaculture is very broad in scope involving a variety of organisms, both freshwater and marine environments, as well as wastewater recycling through natural aquatic habitats (Reference 2). Aquatic macrophytes (water tolerant vascular plants), finfish, invertebrates, and integrated systems are the aquacultural components considered in this assessment. A separate technology assessment covers the subject of wetland systems used for wastewater treatment (Reference 3), and thus are not specifically discussed in this report.

Wastewater aquaculture systems are not a new concept. In many parts of the world, fertilization of ponds with human and animal wastes to increase growth and production of fish has been practiced for centuries (Reference 4). A review of sewage fertilization in fish culture was published by Allen (Reference 5). Recently, increased attention has been given to the improvement of water quality and the waste treatment system capacity by use of designed aquaculture systems. Conferences have stressed the use of wastewaters in food and fiber production (References 6 and 7), and emphasized aquatic biological systems as wastewater purification schemes (References 8 and 9). In 1978, Duffer and Moyer reviewed the developmental status of the aquaculture alternative for wastewater treatment with emphasis given to the reduction or fate of pollutants

(Reference 10). The proceedings of a seminar (Reference 11) and engineering assessment on wastewater aquaculture systems (Reference 12) in 1979 defined the status of aquaculture technologies to determine if they were ready for use in municipal wastewater treatment.

The conversion of wastes by aquatic organisms relies on the same basic biological principles used in aquaculture production systems. In this assessment, the scope is limited to those systems that emphasize the culture of aquatic organisms for wastewater treatment and management. Biomass production or recovery of some other beneficial product is a secondary feature. However, potential economic return from a harvested by-product to offset the costs of wastewater treatment could serve as an incentive to use these alternative systems.

Aquaculture systems are being used for all phases of wastewater treatment from secondary through advanced wastewater treatment. Many current systems use aquaculture components for removal of specific pollutants such as biochemical oxygen demand (BOD), suspended solids (SS), nutrients or metals, or are designed as a polishing step after conventional forms of treatment. The fundamental purpose of aquatic plants and animals, and their management in aquaculture systems, is to improve the rate and/or reliability of one or more of the contaminant removal mechanisms in the aquaculture treatment system (Reference 13).

Interest in aquaculture processes for wastewater treatment is fostered not only in the acknowledgement that wastewater can be viewed as a resource, but also that these processes can be adapted to low technology systems. Although more land intensive, aquaculture systems can potentially be cost competitive with conventional treatment. In some applications they use less energy and non-renewable resources when compared to conventional treatment schemes.

A wide range of managed aquatic biological systems have been considered and investigated for the purpose of wastewater treatment. Systems have included ponds, basins, raceways and other structures which utilize various combinations of aquatic plants and animals. A technical advisory group headed by Duffer and Harlin was established in 1979 to aid in objectively assessing the potential for development of wastewater aquaculture treatment systems. Based on available technology and potential for early payoff, this group reported that the current research and development efforts should be concentrated on aquatic macrophytes (Reference 2). In 1980, Reed et al. concluded that aquatic plant systems, particularly water hyacinths, are ready for routine use in municipal wastewater

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treatment, at least within the geographical range where such plants grow naturally. Fish, invertebrate, and integrated systems are all still in the exploratory or developmental stage and as such, are not ready for routine use (Reference 14). Systems involving higher forms of animals are generally efficient, however they require more land or are more difficult to control than their aquatic plant counterparts. Nevertheless, animal-based systems may find wastewater treatment applications where use of an aquatic plant is limited due to climatic or other constraints (Reference 15).

DETAILED DESCRIPTION

Aquaculture wastewater treatment systems consist of one or more shallow basins, ponds, or raceway in which one or several species of aquatic organisms are cultured. The constructed basins and the systems themselves are generally similar in concept to those employed in wastewater treatment pond technology (Reference 14). Frequently aquatic plants or fish are stocked in the final cells of existing wastewater stabilization ponds. The major physical difference between aquaculture systems and stabilization ponds is the presence of higher aquatic plants and/or animals in addition to suspended planktonic species such as algae (Reference 13).

Aquatic plants, particularly water hyacinths, are used to treat raw wastewater as well as effluents from various stages of conventional treatment units. The most common system incorporates a stabilization pond followed by aquatic plant culturing basins in series (Reference 16). Animal-based aquaculture wastewater treatment systems have been applied to secondary effluent or to its equivalent to produce the effluent quality of secondary or advanced treatment levels. A schematic process-flow diagram of aquaculture wastewater treatment systems is illustrated in Figures 1 and 2.

The selection of aquatic organisms for use in wastewater treatment is based on the degree of pretreatment, the required treatment level, by-product recovery, and the environmental requirements of the candidate species (Reference 13). A summary of selected references dealing with the environmental requirements of potential plant and animals species to be used for the treatment of wastewater has been published by the California State Water Resources Control Board. As part of an overall assessment of wastewater aquaculture (Reference 17), these annotated bibliographies deal with the physical, chemical, and biological parameters of aquatic plants (Reference 18), fish (Reference 19), crustaceans (Reference 20), and freshwater bivalves (Reference 21).

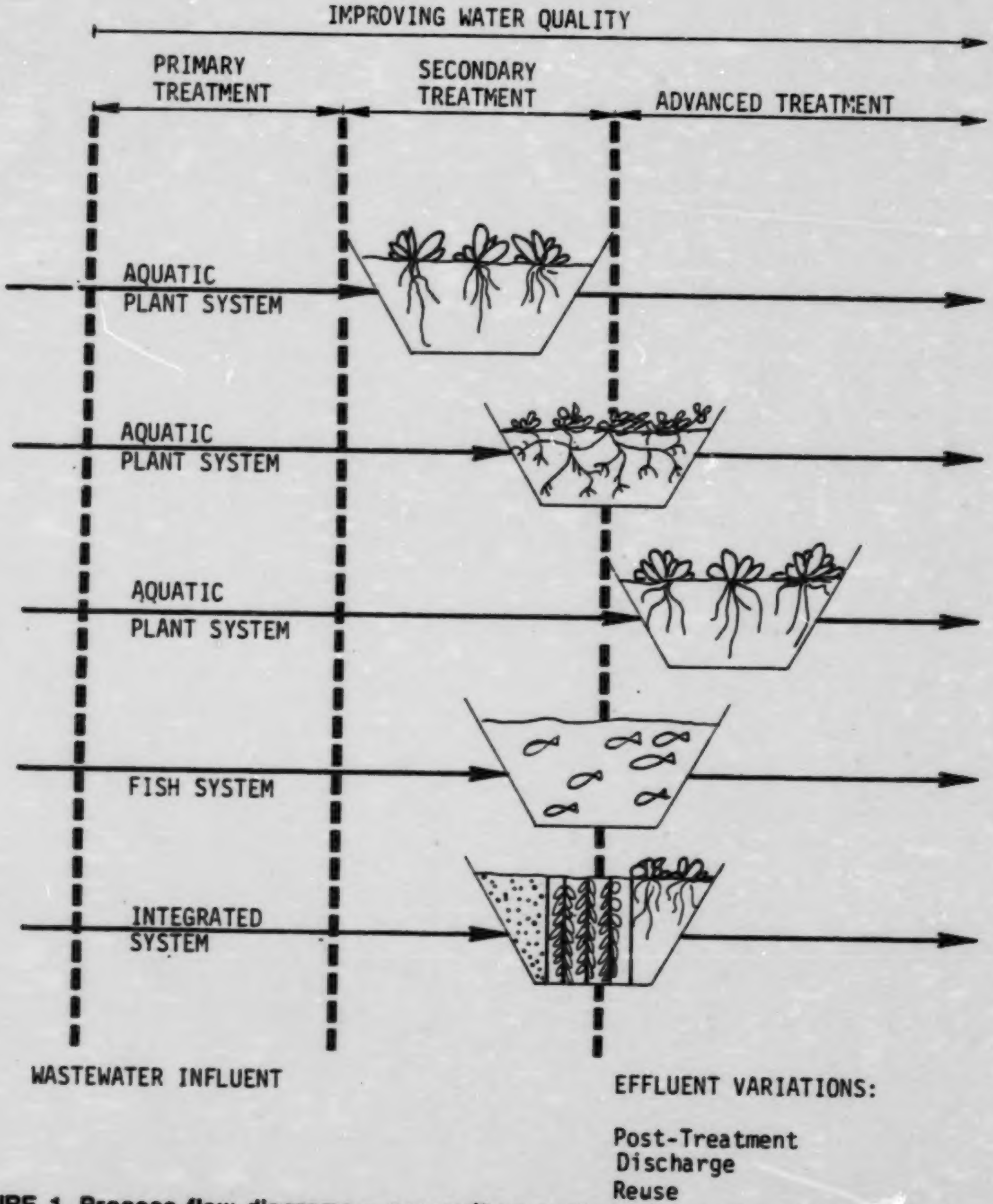
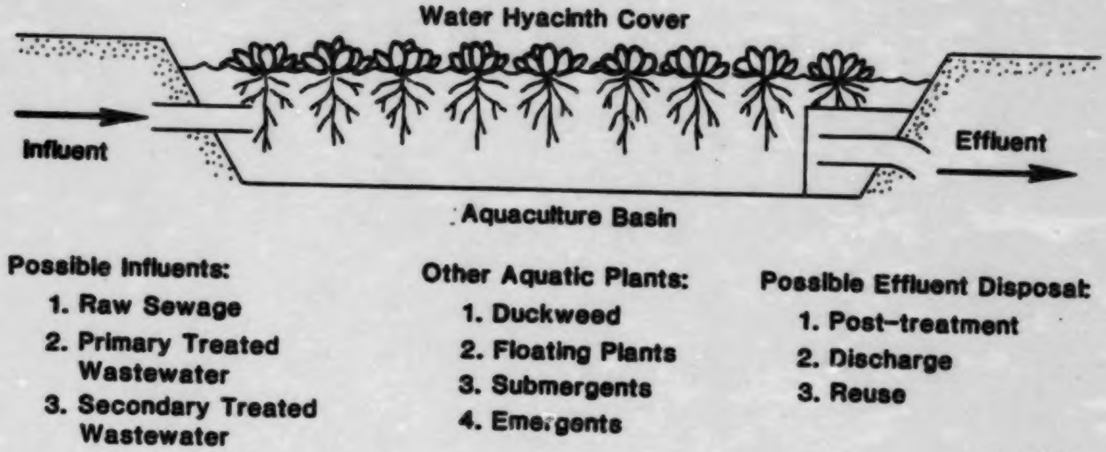
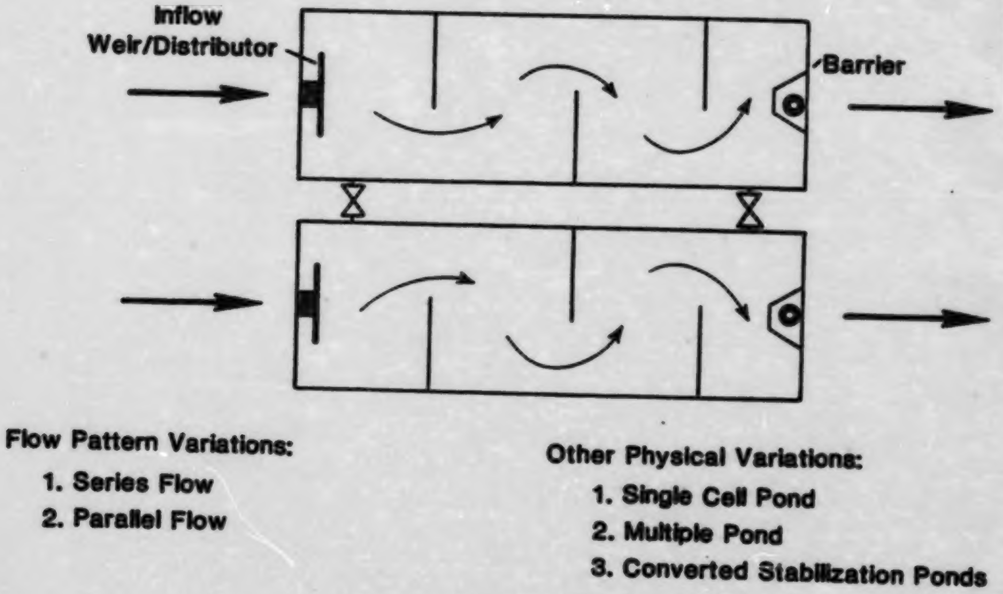

IMPROVING WATER QUALITY
PRIMARY TREATMENT
SECONDARY TREATMENT
ADVANCED TREATMENT
AQUATIC PLANT SYSTEM
AQUATIC PLANT SYSTEM
AQUATIC PLANT SYSTEM
FISH SYSTEM
INTEGRATED SYSTEM
WASTEWATER INFLUENT
EFFLUENT VARIATIONS:
Post-Treatment
Discharge
Reuse

FIGURE 1. Process flow diagrams – aquaculture systems for wastewater treatment.


Water Hyacinth Cover
Influent
Effluent
Aquaculture Basin
Possible Influents:
1. Raw Sewage
2. Primary Treated Wastewater
3. Secondary Treated Wastewater
Other Aquatic Plants:
1. Duckweed
2. Floating Plants
3. Submergents
4. Emergents
Possible Effluent Disposal:
1. Post-treatment
2. Discharge
3. Reuse

A. Schematic


Inflow Weir/Distributor
Barrier
Flow Pattern Variations:
1. Series Flow
2. Parallel Flow
Other Physical Variations:
1. Single Cell Pond
2. Multiple Pond
3. Converted Stabilization Ponds

B. Flow Diagram

FIGURE 2. Aquatic plant wastewater treatment system schematic and flow diagram.

Aquatic Plants (Macrophytes)

All aquatic macrophytes (water tolerant vascular plants) have wastewater treatment potential. Selection of plant species is dependent on the type of aquatic environments necessary to achieve the wastewater treatment objectives and the potential of the plant species to reliably provide necessary components of these environments (Reference 13). A representative variety of aquatic macrophytes that have been studied, or show potential for the reclamation of wastewaters are presented in Table 1. Many aquatic plants need to be tested for wastewater treatment effectiveness, climatic limitations, commercial uses, and yield. The wastewater treatment effectiveness of a wide range of non-aquatic plants utilizing an intensive hydroponic culture system is being tested by Jewell of Cornell University (personal communication). Emphasis has been placed on non-food crops of high value such as ornamentals.

The greatest emphasis has been placed on the utilization of water hyacinths and, to a lesser extent, duckweeds. Most of the information now available on the performance of aquatic plants in wastewater treatment processes is based upon these species. The characteristics of water hyacinths and duckweeds which make these plants suited for wastewater application have been summarized by several researchers (References 22, 23 and 24) and include the following:

- Rapid vegetative growth rates and productivity especially when grown in waste-enriched waters;
- High nutrient and mineral absorption capabilities;
- Harvesting accessibility; as these plants are not rooted, their floating nature facilitates mechanical removal;
- Reasonable nutritive value and inorganic content for potential by-product and economic recovery (animal feed, compost, methane production);
- Extreme hardiness, even in raw sewage;
- Resistance to diseases and insects.

Water Hyacinth, Eichornia crassipies--

Water hyacinth is a perennial freshwater plant with rounded, upright, shiny green leaves and spikes of lavendar flowers. The morphology of a water hyacinth is illustrated

TABLE 1. SELECTION OF POTENTIAL AQUATIC MACROPHYTES FOR USE IN AQUACULTURE WASTEWATER TREATMENT SYSTEMS

Common Name	Scientific Name
Floating Aquatic Plants	
Water hyacinth	Eichhornia crassipes
Duckweed	Lemna spp.
(Lemnaceae family)	Spirodela spp. Wolffia spp.
Water primrose	Ludwigia spp.
Water lettuce	Pistia stratiotes
Water fern	Salvinia spp.
Water velvet	Azolla spp.
Alligator weed	Alternanthera philoxerides
Submerged Aquatic Plants	
Pond weeds	Potamogeton spp.
Oxygen weed	Elodea spp.
Coontail	Ceratophyllum spp.
Watermilfoil	Myriophyllum spp.

schematically in Figure 3. The petioles are spongy, with many air spaces, and are often swollen, contributing to the bouyancy of the plant in its free-floating state. Roots, leaves, and inflourescence (the characteristic arrangement of flowers on a stalk or cluster) arise from a vegetative stem or rhizome having short internodes. Underwater rhizomes, or stolons, connect plants to each other and dense mats of plants frequently form.

Native to South America, water hyacinths occur in slow moving or stagnant freshwaters throughout the tropics and subtropic regions of the world. The geographical area in which these plants thrive is bounded by 32°N and 32°S latitude. Introduced into the United States in 1884, the species spread

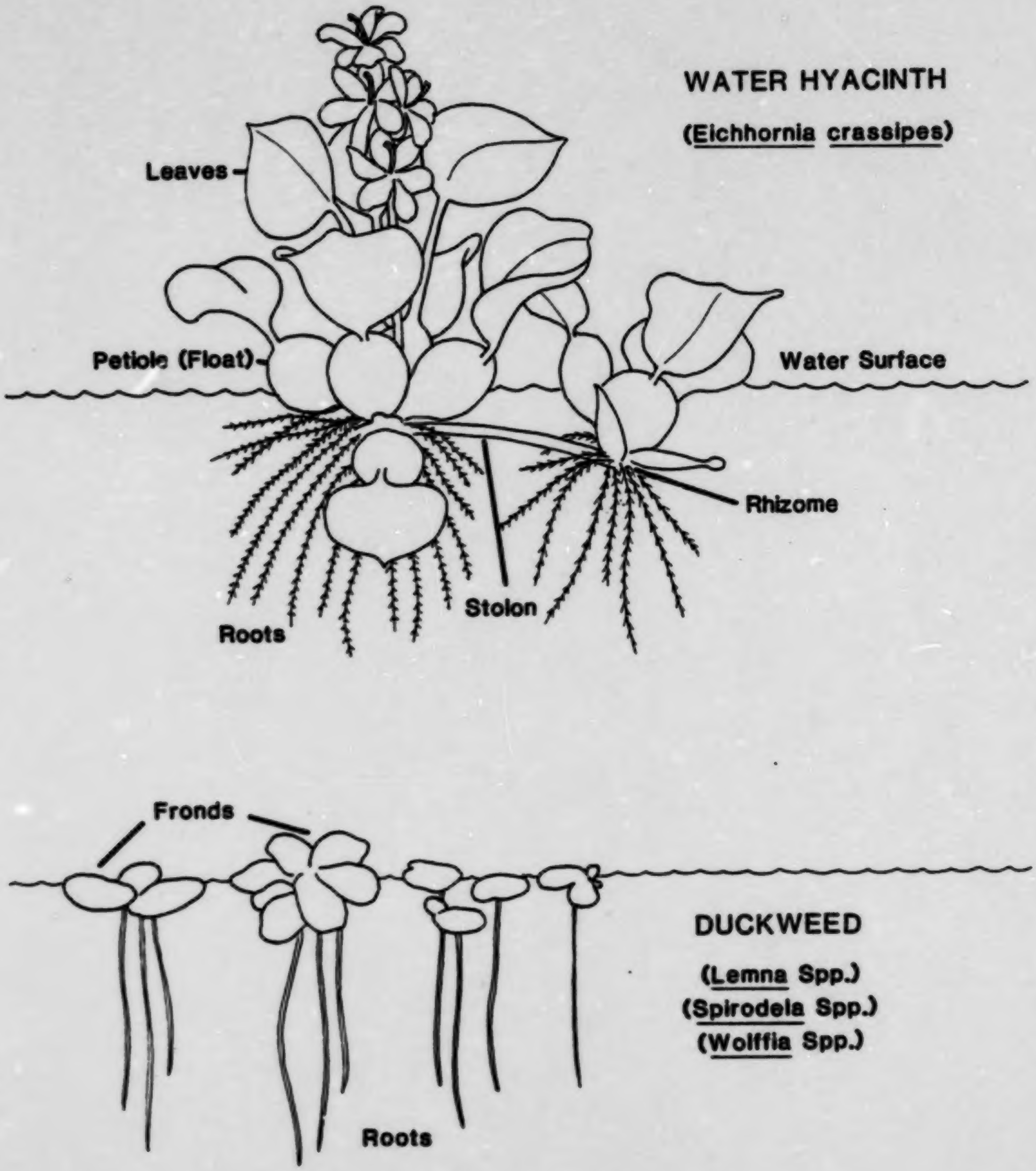

WATER HYACINTH
(Eichhornia crassipes)
Leaves
Petiole (Float)
Water Surface
Rhizome
Stolon
Roots
Fronds
DUCKWEED
(Lemna Spp.)
(Spirodela Spp.)
(Wolffia Spp.)
Roots

FIGURE 3. Morphology of water hyacinth and duckweed.

rapidly and became established in waterways of several southern states. Due to its rapid vegetative growth and prolific nature, infested waterways prevented water movement and navigation. Weed control programs, dating back to 1900, involved mechanical procedures later replaced by the use of herbicides. These efforts involved the expenditure of millions of dollars and generated extensive technical literature.

The water hyacinth is probably the most intensively studied aquatic plant to date. In 1948, Penfound and Earle conducted life history study of hyacinths (Reference 25). Pieterse published a review article in 1975 on water hyacinths covering all aspects of research that have been accomplished, including sections on general botany, ecology and plant growth; chemical biological and mechanical control; chemical composition; utilization of the plant for by-products, and use for the removal of minerals and pollutants from wastewater (Reference 26).

There are several environmental factors affecting water hyacinth growth. The most significant is temperature. The optimum water temperature ranges from 20° to 30°C, with growth ceasing below 10°C and above 40°C. Freezing temperature will kill the leaves and stems of the plant above water. However, the plant can regenerate from the rhizomes when weather conditions improve, providing the rhizomes are not frozen. Air temperatures lower than -2.2°C will usually kill the rhizomes (Reference 25). This restricts the area of uniform year-round plant growth in the natural environment to southern Florida and southern Texas (Reference 27). Throughout the remainder of the United States, active growth occurs from seven to ten months per year.

Water hyacinths are also intolerant to salt water, and will die in waters with salt concentrations of 2.2 parts per thousand (Reference 28). Hyacinth plant growth is also related to the available concentration of nutrients, particularly nitrogen, in the water (Reference 22).

Water hyacinth growth rates and productivity have been investigated by several researchers. Unfortunately, many different terms and units of measure are used to describe plant production, resulting in data difficult to compare. Also wide variations for growth responses contained in the literature are partly due to differences in the environments encountered in natural systems and in the enriched media provided by wastewater (Reference 29).

Early growth rate studies by Penfound and Earle (Reference 25) in natural environments were used by Westlake in estimating the annual productivity of water hyacinth to be 10 to 30 metric

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tons/ha, dry-weight, with projections of possible maximum annual production rates of 100 to 136 metric tons/ha/yr, dry-weight, under ideal conditions (Reference 30). A study by Wooten and Dodd found a production of 27 metric tons of organic matter/ha in only 105 days (Reference 31). Wolverton and McDonald later projected an annual productivity of 140 dry metric tons/ha from growth rate studies at a wastewater lagoon in southern Mississippi (Reference 32). Measured yields of 80 dry metric tons/ha/yr were reported in central Florida under optimum conditions (Reference 33).

Besides being one of the most productive photosynthetic plants, water hyacinths are prolific, reproducing primarily by vegetative means. Cornwell determined that the average doubling rate for a mass of hyacinths was approximately six days (Reference 34). It was estimated that in an eight month growing season, ten plants could produce 600,000 and cover one acre of water (Reference 25). Individual plant measure from 50 to 120 cm, root tip to the top of the flower cluster, when grown in wastewater (Reference 35).

The major constituent of water hyacinth biomass is water, contributing approximately 95 percent of the weight of the plant. The dry weight composition of water hyacinths removed from a wastewater treatment system is presented in Table 2.

TABLE 2. DRY WEIGHT COMPOSITION OF WHOLE WATER HYACINTH PLANTS GROWN IN WASTEWATER (References 11 and 32)

Parameter	Percent of Dry Weight Average	Percent of Dry Weight Range
Crude Protein	18.1	9.7 - 23.4
Fat	1.88	1.59 - 2.20
Fiber	18.6	17.1 - 19.5
Ash	16.6	11.1 - 20.4
Carbohydrate*	44.8	36.9 - 51.6
Kjeldahl Nitrogen (as N)	2.90	1.56 - 3.74
Phosphorus (as P)	0.63	0.31 - 0.89

*Computed by mass balance

Duckweeds--

Members of the duckweed family (Lemna spp., Spirodela spp., and Wolffia spp.) are all small green plants, with individual structures and fronds, less than one centimeter in length. The morphology of duckweed is illustrated in Figure 3. The plants float at or just below the surface of relatively still, fresh water. Occurring world-wide, duckweeds have a wider geographic range than water hyacinths. They vegetate at temperatures above 1° to 3° and winter well (Reference 24). Some duckweeds grow in brackish water.

Duckweeds (Lemna spp.) grown at 27°C under laboratory conditions in wastewater effluent were reported to double in frond number, and thus in area, every four days (Reference 36). The dry weight of duckweed grown under these conditions was 0.25 metric tons/ha. Ryther reported an annual yield of 12.2 metric tons/ha/yr., dry weight, for Lemna sp. in a medium of enriched well water under optimum conditions (Reference 33). Hillman and Culley reported an annual dry-weight production of mixed duckweed populations on a wastewater lagoon in the southern United States of 17.6, with a maximum of 24.5, dry metric tons/ha/yr (Reference 24).

Duckweed, like water hyacinth, contains approximately 95 percent water in the plant tissue. The composition of this tissue is summarized in Table 3.

TABLE 3. DRY WEIGHT COMPOSITION OF DUCKWEED PLANTS GROWN IN WASTEWATER (References 24, 29, 37)

Parameter	Percent of Dry Weight Average	 Range
Crude Protein	38.9	32.7 - 44.7
Fat	4.9	3.0 - 6.7
Fiber	9.4	7.3 - 13.5
Ash	15.0	12.0 - 20.3
Carbohydrate*	35.8	- -
Kjeldahl Nitrogen (as N)	5.91	4.59 - 7.15
Phosphorus (as P)	1.37	0.80 - 1.8

*Computed by mass balance

Fish

Fish species for culture in wastewaters historically have been chosen for production of a valuable product rather than as a means of wastewater treatment. Limits in culture capability have contributed to the complexities of obtaining both objectives (Reference 10). Species of fish that have been used in wastewater treatment experiments are described in Table 4.

Fish biomass produced by feeding on an algae and invertebrate biomass represents a removal of nutrients that would otherwise be discharged in the effluent. Fish species that feed lower on the food chain offer greater potential for the treatment of wastes and resource recovery. Polyculture systems, the use of different trophic levels, combine several species of fish for wastewater treatment. The combination of pure plankton feeding fishes, filamentous algae eaters, bottom feeders, or scavengers also offers greater treatment potential than a monoculture system.

Because fish physiology is regulated to a great extent by the aquatic environment with which they are in contact, the selection of fish species for the treatment of wastes requires an understanding of the environmental requirements of the candidate species (Reference 19). As fish are temperature conformers, temperature has the greatest effect on the physiology of fish of any of the environmental variables. Thus, water temperature has a significant effect on food intake, digestion, growth, and behavior. Dissolved oxygen is another of the limiting parameters for fish. For each species there exists a critical oxygen level, but in most cases, dissolved oxygen concentrations less than 2 mg/l are limiting to fish and concentrations below 5 mg/l promote slow growth. Other physical parameters to be considered include light intensity, photoperiod, and gas supersaturation.

The nitrogenous compound ammonia is highly toxic to fish. Sublethal or lethal levels may accumulate in wastewater due to either the metabolic wastes excreted by aquatic animals or from human wastes or other sources. The pH tolerance of fish ranges from 6.5 to 9 and will not be a significant parameter under normal conditions. Other chemical parameters, such as salinity, heavy metals, toxics, etc., also affect the growth and survival of fish.

A group of fishes known as Chinese carp, which include the silver, bighead, black, and grass, carp, and the European common carp (see Table 4) may be considered the most likely candidates for achieving the objective of wastewater treatment. These fish possess the feeding habits (described in Table 4) that meet the biological considerations for wastewater purifi-

TABLE 4. FISH SPECIES USED IN AQUACULTURE WASTEWATER TREATMENT SYSTEMS (References 38, 39 and 40)

Common Name	Scientific Name	General Living Area in Pond	Feeding Habits
Silver Carp	*Hypophthalmichthys molitrix*	Fast swimming in upper layers	Phytoplankton (down to 20 microns in size or less)
Bighead Carp	*Aristichthys nobilis*	Slow moving in upper layers	Phytoplankton, zooplankton, suspended detritus
Black Carp	*Mylopharyngodon piceus*	Bottom	Snails, mussels, crustaceans
Grass Carp	*Ctenopharyngodon Idella*	Ubiquitous	Variable, but able to consume a wide variety of plant material
Common Carp	*Cyprinis carpio*	Bottom	Phytoplankton, zooplankton, insect larvae
Tilapia	*Tilapia* Spp. *Sarotherodon* Spp.	Ubiquitous	Aquatic plants, plankton, detritus, and invertebrates
Catfish	*Ictalurus* Spp.	Bottom	Planktonic crustaceans, algae, insect larvae, fish
Minnows Fathead minnows Golden shiner	Cyprinidae family *Pimephales promelas* *Notemigonas crysoleucas*	Bottom Fast swimming in upper layers	Phytoplankton, zooplankton, invertebrates
Mosquito Fish	*Gambusia affinis*	Surface layers	Variable; algae, zooplankton, insect larvae
Buffalofish	*Ictiobus* Spp.	Bottom	Planktonic crustaceans, detritus, insect larvae

cation; but, the most important consideration is their hardiness and adaptability to a wide range of environmental conditions (References 38 and 39).

Invertebrates

A variety of animal organisms that feed directly on phytoplankton cultured in ponds receiving wastewaters has been studied in an effort to develop a biological method for the clarification and purification of these waste effluents (Reference 10). Those organisms evaluated include Daphnia and related species (water fleas), Artemia (brine shrimp), and assorted bivalve mollusks (oysters, clams, and mussels).

The environmental parameters considered in the selection of fish species for wastewater aquaculture treatment systems are also applicable to invertebrate species.

Integrated Systems

Experimental systems that combine several types of organisms rather than focusing on one or two types of organisms for treatment or utilization of wastewater are referred to as integrated systems (Reference 10). These treatment systems derived from aquaculture concepts may either contain more than one active component in a single unit or a combination of aquaculture components to form a process. Such systems are highly structured and often display complex food chain interrelationships.

Culture Basins

Culture basin size, number, and configuration are determined by the degree of pretreatment of the influent and also the discharge requirements of the effluent. The following characteristics of an optimal aquatic plant culture basin are based upon current experience with experimental systems in operation and upon recommendations by Dinges (Reference 41) and Wolverton (Reference 42). An engineering design manual recently made available by Gee and Jenson Engineers outlined the factors to be considered and evaluated in constructing a water hyacinth treatment system (Reference 43). Most aquatic animal-based systems studied have used existing lagoons, and hence, specifics on optimum number, size, and configuration of culture basins have not been established (Reference 15).

The majority of aquatic plant systems studied to date have been designed to operate with three basins in series. Single cell stabilization ponds, however, with water hyacinth coverage have been employed successfully. If the objective is the control of algae in the effluent from a wastewater stabilization pond, then a single basin appears to work just as effectively as the series arrangement. A minimum of two separate ponds, each having a capacity to treat the average daily flow, has been recommended. Such a dual aquatic plant system would allow for periodic cleaning and maintenance without any interruption of treatment.

By their very nature, animal-based and integrated aquaculture systems require multiple basins, and the optimum number of basins to be used is dependent on individual circumstances. Specific reasons for the use of multiple cells would include among others, the need to regulate food chain relationships, maintain proper culture population, and control the level of dissolved oxygen (Reference 15). In addition, these systems should be designed to allow maximum operational flexibility and uninterrupted services when any basin must be taken out of operation for cleaning or other maintenance purposes.

The most critical design factors for water hyacinth basins noted by Dinges were the rate of flow of wastewater through the basin and uniform distribution of wastewater at inlet and outlet zones (Reference 41). Thus, broad rectangular basins having a length to width ratio of at least 3:1 have been recommended. This configuration minimizes short-circuiting, wind effects, and eliminates variations in treatment efficiency.

Individual basin size, width, and depth, are set allowing for efficient harvesting and routine maintenance. A maximum basin width from 15.2m (50 ft.) to 30.4m (100 ft.), with a minimum of 7.6m (25 ft.), is recommended, dependent on the type of harvesting equipment available. Individual basin size of a maximum of 0.4ha (1 acre) has also been recommended. Mean basin depths have varied from 0.38m (1.25 ft.) to 1.83m (6 ft.) with a depth of 0.91m (3 ft.) or less recommended. A critical concern is to provide adequate depth for the development of the floating plant/root system. Systems designed for nutrient removal have used a depth of approximately 0.4m (1.25 ft.) to ensure complete contact of the wastewater with the root system (Reference 16).

Culture basins are constructed by excavating and diking the required area. Berms designed for easy maintenance and harvesting should have a top width of 3m (10 feet), and sides with a vertical to horizontal slope of 1:3. The berms are compacted to prevent seepage or keyed into an impervious soil layer if leakage through a sandy topsoil is expected. Minimum freeboard above the design water level should be at least two feet. In areas with a high groundwater table, it may be necessary to seal the pond bottom. This can be accomplished with clay, cements, plastic liners, or asphalt. A slope of at least 0.5 percent from the upper end to lower end of the basin, and a sump excavated at the lower end, would facilitate rapid drainages.

Inlet and outlet structures and piping in each pond should be designed to distribute flow evenly across the pond. For small basins, a single inlet and outlet centered on the short sides of the basins is suitable. In larger ponds, multiple inlets, such as perforated pipes, and outlets or continuous weirs have been recommended. Inter-connecting piping between ponds would provide maximum operation flexibility and allow parallel or series operation. All piping should be valved and drains provided in each pond. A fixed barrier of screening, or a crushed rock or gravel dike around the outlet can serve to retain the plants, allow for reaeration, and prevent the discharge of plant debris.

Supplemental mechanical aeration, such as surface aerators, have been used in aquatic plant basins. Submerged aeration lines, consisting of lead-weighted valved polyethylene tubing, have been used in both aquatic plant and fish culture basins.

COMMON PROCESS MODIFICATIONS

Common process modifications include the following:

- Basin Size and Configuration: Variation may occur when land to be used is odd-shaped or when an existing lagoon system is to be redesigned.

- System Enclosures: Greenhouse-type protective covers allow the extension of aquatic plant systems to climatic zones where plants cannot exist naturally or where plant growth is seasonal.

- Heating Basin Waters: Sources of heat which might be used to warm culture basin waters could include methane produced from harvested biomass, cooling waters, solar panels or refuse incineration (Reference 41).

- Chemical Removal of Phosphorus: The addition of alum, ferric chloride, or other chemicals can remove phosphorus remaining in the effluent from tertiary aquatic plant systems.

- The aquatic plant treatment process may also be suited for seasonal use in treating wastewaters from recreational facilities and those generated from processing of agricultural products. Other potential uses might include renovation of small lakes and

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reservoirs, pretreatment of surface waters used for domestic supply, storm water treatment, demineralization of water, recycling fish culture waters, and biomonitoring purposes (Reference 41).

SECTION 2

RECOMMENDATIONS

The use and reliability of aquaculture processes in wastewater treatment systems should increase as successful experience is gained in the future. Costs are expected to become more competitive with conventional treatment systems as aquaculture systems become optimized. Based on this assessment, the following recommendations are made regarding the implementation of aquaculture systems for wastewater treatment:

- Construction and Design of Aquaculture Basins. Various methods of basin construction should be studied to determine the most cost-effective methods. The design of the basins should be optimized to minimize energy requirements and facilitate minimum maintenance of the basins.

- Engineering Design Criteria. Research projects should be developed to test design criteria (i.e., surface and organic loadings). This information is necessary for the design of various types of aquaculture system.

- Labor Requirements. Available information regarding O&M labor requirements is limited. Operating facilities should document actual labor requirements to enable other agencies to accurately estimate labor demands and review operational procedures.

- Costs. Accurate documentation of the construction and O&M expenses should be maintained by operating facilities. This information would be helpful for future cost estimates. Existing documentation of costs is poor.

- Suitability of Specific Systems to Geographical Regions. A guide should be developed to identify geographical regions best suited for various aquaculture system types and plant and animal species.

- Performance Data. Performance data for BOD, SS, nitrogen, phosphorus and coliform have been collected and published for some of the full scale facilities, but this should also have been done for all of the full scale facilities. Additional parameters that also should be monitored are total solids, dissolved solids, suspended solids, COD, heavy metals, refractory organics, and pathogens.

- Information Transfer. Publication of successful project information in widely read professional publications is needed to inform wastewater agencies of aquaculture wastewater treatment opportunities. Guidance documents published by EPA for distribution by state and regional regulatory and funding agencies to wastewater management agencies would be useful in promoting aquaculture technology. Currently, many state and regional agencies are not well informed regarding the application of aquaculture technology.

- Research and Development Needs. Water hyacinths have emerged as the primary aquaculture mode due to the historical interest and development of this technology by aquatic biologists. Alternative systems (e.g. other plant species) have not received similar attention and, therefore, are not at the same level of development. Research and development of alternative plant systems that overcome the constraints of water hyacinths are needed to spur more widespread use of aquaculture systems for wastewater treatment.

SECTION 3

DEVELOPMENTAL STATUS OF AQUACULTURE SYSTEMS

SUMMARY OF RESEARCH FINDINGS

The developmental status of each of the four specific aquaculture systems (aquatic macrophytes, invertebrates, fish and integrated systems) are presented individually.

Aquatic Macrophytes

Summary of Research Findings--

The status of water hyacinths in wastewater treatment has progressively developed during the past few years of research. Water hyacinths have been extensively studied at the laboratory level and tested at the pilot scale level. Continuation of these efforts has produced a number of full-scale experimental and demonstration systems for treating primary effluent, for upgrading existing systems, for advanced secondary treatment, and for full advanced wastewater treatment.

Wastewater treatment experience with duckweeds has not been as extensive. Research with other aquatic plants has been limited.

Bench Scale Research--

Based on theoretical projections from observed plant nutrient content and potential productivity, water hyacinths were suggested as excellent candidates for nutrient removal systems by several researchers. Boyd calculated that 1,980 kg/ha of nitrogen and 322 kg/ha of phosphorus could be removed per year by a continual culture of water hyacinths (Reference 23). Steward estimated that 0.4 ha (1 acre) of water hyacinths could potentially utilize all of the nitrogen fraction contained in the secondary treated wastewater of 130 to 595 people with corresponding growth rates estimated at 6 to 27 dry metric tons/ha/yr (Reference 44). At the same estimated growth rates, the phosphorus production of 40 to 180 people could be used. These nutrient removal potentials were based on the yearly per capita contributions of 4kg (9 lbs.) N, and 1.4 kg (3 lbs.) P.

Projections of this nature were further substantiated in actual nutrient removal studies. A variety of laboratory experiments were designed to determine the absorption of nitrogen and phosphorus by water hyacinths. Rogers and Davies studied the changes in nitrogen and phosphorus concentrations in batch and continuous flow cultures containing a single water hyacinth plant (Reference 45). Based on their findings and estimates of annual domestic wastes per capita of 3.2 kg N and 0.9 kg P, they projected that 1 ha of water hyacinths (approximately 1.62×10^6 plants) could uptake an amount of nitrogen and phosphorus equivalent to the wastewater from over 800 persons. An 86 percent reduction of phorphorus from an initial concentration of 1.4 mg/l to 0.2 mg/l by water hyacinths grown in sewage effluent under batch conditions for a five-week period was noted by Ornes and Sutton (Reference 46). In another study, Sheffield found that a laboratory scale system, consisting of a water hyacinth pond followed by an air stripping and coagulation unit receiving 8.0 liters/day of secondary treated wastewater, could reduce ortho-phosphates to 0.7 mg/l, nitrate nitrogen to 0.2 mg/l, and ammonium nitrogen to 0.1 mg/l from initial concentrations of 60, 10, and 23 mg/l, respectively (Reference 47). Scarsbrook and Davis reported that water hyacinths absorbed 2.87g of phosphorus, 6.93g of nitrogen, and 8.73g of potassium during a 23-week period batch study when grown in sewage effluent contained in pools 2.7m in diameter and 0.7m in depth (Reference 48).

Laboratory investigations on the pollution removal capabilities of water hyacinths were conducted by Wolverton (Reference 49). Table 5 summarizes the reductions in wastewater constituents in 5-liter cylinders containing hyacinths and domestic sewage. Alligator weeds were also tested under the same conditions and demonstrated ability to remove nutrients and pollutants from domestic wastewater.

Recent laboratory experiments by Wolverton were conducted to correlate BOD_5 removal with known wet masses of water hyacinths (Reference 42). Data from these experiments using domestic wastewater indicated that an average total BOD_5 removal rate of 4.0 mg BOD_5/gram wet weight of hyacinths could be achieved with a seven-day retention time.

The ability of water hyacinths to remove chemical and metal pollutants has also been documented under laboratory conditions (Reference 51, 52, 53, 54 and 55). Table 6 summarizes these capabilities.

TABLE 5. PERCENT REDUCTIONS IN WASTEWATER CONSTITUENTS UTILIZING WATER HYACINTHS UNDER BATCH LABORATORY CONDITIONS (Reference 49, 50)

	Precent Reduction in Wastewater Constituents					
	Raw Sewage		Secondary Effluent			
	7-Day Exposure		7-Day Exposure		14-Day Exposure	
Measurements	W/Plants	Control	W/Plants	Control	W/Plants	Control
Total Kjedahl Nitrogen	92	18	75	13	89	15
Total Phosphorus	60	13	87	11	99	25
Total Suspended Solids	—	—	75	15	77	12
BOD_5	97	61	77	6	—	—

TABLE 6. CAPABILITY OF WATER HYACINTHS TO REMOVE VARIOUS CHEMICAL AND METAL POLLUTANTS FROM WATERS (References 51, 52, 53, 54 and 55)

Chemical and Metal Pollutants	LABORATORY EXPERIMENTS mg of Pollutant Removal per gram of Dry Plant Material per day	FIELD POTENTIAL kg of Pollutant Removed/acre/day*
Cadmium	0.67	0.161
Cobalt	0.57	0.137
Lead	0.18	0.042
Mercury	0.15	0.036
Nickel	0.50	0.120
Silver	0.65	0.156
Strontium	0.54	0.130
Phenols	36	8.640

*Based on removal of mature plants every 24 hours.

Duckweeds have been investigated less extensively than water hyacinths under laboratory conditions. Harvey and Fox reported that *Lemna minor* removed substantial amounts (86 percent and 67 percent) of total kjeldahl nitrogen and total phosphorus from 22 liters of secondary wastewater effluent for a 10-day test period (Reference 56). Sutton and Ornes obtained over a 90 percent reduction in the phosphorus content of sewage effluent over an eight-week growth period using a mixed population of *Lemna* spp. (Reference 57) in a batch system. The same investigators, using *Spirodela polyrhiza*, reported a reduction from 3.53 ug/l to 0.09 ug/l, representing a 97 percent decrease in the phosphorus content of secondarily treated wastewater effluent studied in batch conditions during a 12-week test period (Reference 58).

A laboratory investigation to determine the wastewater treatment effectiveness of a variety of aquatic macrophytes has been initiated by EPA's R.S. Kerr Environmental Research Laboratory (personal communication with Dr. W.R. Duffer, principal investigator). Batch screening tests have been conducted with six species of aquatic plants utilizing primary and secondary effluents. Bench scale flow tests for species having best survival and showing most promise for removal of pollutants were undertaken in 1981.

Pilot Scale Research--

The ability of water hyacinths to remove BOD_5, suspended solids, and other pollutants as well as inorganic nutrients from wastewaters has been reported in pilot-scale studies by numerous investigators. Systems providing both secondary and advanced wastewater treatment have been studied. In 1965, Furman and Gilcreas reported reductions of approximately 75 percent in organic and ammonia nitrogen by water hyacinths grown in the third cell of a four-celled raw wastewater oxidation pond having detention time of five days (Reference 59). The plant-covered cell had an area of 0.2 ha (0.5 acre) and averaged 1.07m (3.5 ft.) in depth. Clock reported that, at a detention time of five days, nitrates were reduced 75 percent and phosphates were reduced 61 percent when secondary wastewater effluent was in contact with a dense mat of growing hyacinths (Reference 60).

In 1969, Sheffield and Furman studied nutrient removal in secondary wastewater effluent passed through a hyacinth pond and reported removals of 92 percent of nitrate, 35 percent of ammonia, and approximately 50 percent of orthophosphates (Reference 61). Minor, using hyacinth ponds to treat swine manure, reported that the plants removed 10.4 kg (23 lbs) of ammonia nitrogen, 11.4 kg (25 lbs) of Kjeldahl nitrogen, and 7.72 kg (17 lbs) of phosphates per acre (0.405 ha) with a 102-day detention time in ponds 46 cm (18 in.) deep (Reference 62).

Neuse observed BOD_5 reductions of 67 percent and total suspended solids reductions of 79 percent in a study conducted with stabilization pond effluent (Reference 63).

More recent and extensive pilot studies were conducted by a group of scientists and engineers at the University of Florida at Gainesville; the Texas Department of Health Resources in Austin; and the National Aeronautics and Space Administration (NASA) at the National Space Technology Laboratories in Bay St. Louis, Mississippi. Results from the water hyacinth system studied by these investigators are discussed further, along with a single study involving duckweed.

A three-phase water hyacinth study was carried out between 1971 and 1974 at the University of Florida at Gainsville (Reference 64). The third cell of a polishing pond system with a total surface area of 2,323 sq m (25,000 sq ft.) and an average depth of 1.4m (4.5 ft.) was used for the first two phases of the study. Receiving secondary effluent from a treatment facility on campus, the flow into the test pond was approximately 1900 cu m/d (0.5 mgd) with a surface loading rate of 0.25 cu m/sq m/day (3.70 acres/mgd). The detention times were varied from 6 to 24 hours to observe their effects on nutrient removal. Nutrient removal was below desired levels at the low detention times and large depths tested, but results of the study indicated that both detention time and depths were important in nutrient removal by water hyacinths. Therefore, in the third phase of the study three 9.3 sq m (100 ft.^{2}) ponds were constructed with depths of 0.34, 0.64, and 0.70 m (1.1, 2.1 and 2.3 ft.) to evaluate the effects of varying depths and detention times.

Nutrient reduction rates from this third stage were significantly higher than those observed in the first two phases of the study. Results of Phase 3 studies are summarized in Table 7. Surface loading rates for any specific pond depth were directly related to nutrient removal rates.

A two-phase study was initiated in June, 1975, at the Williamson Creek Wastewater Treatment Facility in Austin, Texas (References 65 and 66). The City of Austin provided an experimental hyacinth culture basin, 9.1 m (30 ft.) in width and 64 m (210 ft.) in length, and divided into four sections by crushed stone barriers. Secondary wastewater inflow to the system was maintained at 109 cu m/day (28,800 gpd) for both study phases. Surface organic loading was 43.4 kg/ha/day of BOD_5 (38.7 lbs/acre/day) during the first phase. Mean water depth was 1 meter (3.3 ft.) and theoretical system detention time was 5.3 days for the first phase. Water with a surface organic loading of

TABLE 7. SUMMARY OF NUTRIENT DATA FROM THREE TEST PONDS DURING PHASE 3 OF THE PILOT STUDIES AT THE UNIVERSITY OF FLORIDA FROM JULY, 1973 TO JUNE, 1974 (Reference 64)

Nutrient	Average Influent Value (mg/l)	Detention Time (hours)	Average Effluent Concentrations (mg/l)		
			0.34 m Pond	0.67 m Pond	0.70 m Pond
Total Phosphorus as P	3.44	12	3.42	3.55	--
		24	2.86	3.08	3.33
		48	1.82	2.30	2.90
		96	--	--	1.95
Total Nitrogen as N	13.86	12	12.05	12.48	--
		24	5.89	7.95	11.49
		48	2.72	4.98	6.85
		96	--	--	3.09

8.93 g/sq m/day of BOD_5(79.7 lbs/acre/day) was used in the second phase. Mean water depth was 0.85 m (2.8 ft.) and detention time was 4.5 days for Phase 2.

Table 8 presents the water quality data obtained from this pilot study. The standing crop of hyacinths at the end of the growing study phase represented a dry weight biomass production of 3,184 g/cu m.

NASA has been using higher aquatic plants to upgrade domestic wastewater treatment lagoons and treat chemical wastewaters for the past seven years (Reference 22). Studies have also been conducted in using aquatic plants to recycle waste in future space stations (Reference 67). In addition to upgrading all wastewater treatment systems at the National Space Technology Laboratories (NSTL) by using water hyacinths and duckweeds, NASA has conducted several field studies with local communities in southern Mississippi (Reference 42).

Water hyacinths were introduced into a single cell lagoon at NSTL in June, 1976 (Reference 68). Receiving a relatively light load (TSS 112 mg/l, BOD_5 79 mg/l), the facultative lagoon served a population of 2,000. Background data revealed that the existing lagoon did not meet secondary standards set for BOD_5 and suspended solids. Results during a 14-month hyacinth covered study period showed that the operation of the system was improved when hyacinths assumed a primary role. Another

TABLE 8. SUMMARY OF AVERAGE WATER QUALITY PARAMETERS AFFECTED BY WATER HYACINTH TREATMENT IN PILOT STUDIES AT WILLIAMSON CREEK, TEXAS (References 65 and 66)

	First Study Phase June 1975 - February 1976			Second Study Phase May 1976 - August 1976		
	Influent	Effluent	% Reduction	Influent	Effluent	% Reduction
BOD_5, mg/l	22.6	5.2	77	46.5	5.7	87
TSS, mg/l	43.3	7	84	117	7.5	93
TN, mg/l	8.2	2.5	69	9.9	3.6	63
TP, mg/l	5.6	4.4	21	6.9	5.8	15
Fecal Coliform Bacteria/ 100 ml	2,895	31	—	27,423	363	—

one-cell facultative lagoon located at Lucedale, Mississippi, was studied extensively with and without water hyacinth coverage (Reference 69). Again, the most significant overall improvement in the effluent quality occurred with complete coverage of hyacinths. A complex lagoon system at Orange Grove, Mississippi, was used for conducting a 12-month study with water hyacinths in effluent from aerated lagoons (Reference 22).

A pilot scale duckweed study is being conducted using a two-cell lagoon system located at Cedar Lake development in North Biloxi, Mississippi (Reference 42). Duckweed coverage of the second, unaerated cell occurred through natural means and NSTL began monitoring the system in April, 1979. Design characteristics and performance data for this system and the water hyacinth pond systems studied by NASA/NSTL are summarized in Table 9.

Aerobic ponds populated principally by submerged aquatic plants (*Potamogeton foliosus*, *Elodea canadensis*, and *Ceratophyllum demersum*) were evaluated as part of a field-scale research facility at Michigan State Universtiy, East Lansing, to define wastewater processing limits imposed by ecological mechanisms in both aquatic and terrestrial systems (Reference 70). A series of four ponds ranging from 3 to 5 ha (1.2 to 2 acres) with a total surface area of 16 ha (40 acre) and a mean

TABLE 9. SUMMARY OF DESIGN AND PERFORMANCE CHARACTERISTICS OF THE PILOT WASTEWATER TREATMENT SYSTEMS USING AQUATIC PLANTS STUDIED BY NASA/NSTL (References 16, 22, 42, 68, 69)

Criteria	Location			
	National Space Technology Lab.	Lucedale, Mississippi	Orange Grove, Mississippi	Cedar Lake, Mississippi
Types of Pretreatment	None	None .	2 Aerated Lagoons	1 Aerated Cell
Flow cu m/day	475 (0.125 mgd)	937 (0.247 mgd)	1000 (0.264 mgd)	49 (0.013 mgd)
Surface Area ha	2 (5 acres)	3.6 (9 acres)	0.28 (0.69 acre)	0.07 (0.17 acre)
Depth cm	122 (4 feet)	173 (5.7 feet)	183 (6 feet)	150 (5 feet)
Hydraulic Loading cu m/ha	240 (25,660 gal/acre)	260[a] (27,800 gal/acre)	3570 (381,670 gal/acre)	700 (74,840 gal/acre)
Hydraulic Residence Time/Days	54	67[a]	6.8	22
Organic Loading kg/ha/day	26 (23 lb/acre/day)	44 (39 lb/acre/day)	179 (160 lb/acre day)	31 (28 lb/acre/day)
Plant Cover Percent	Hyacinth 100	Hyacinth 100	Hyacinth 100	Duckweed 100
BOD_5, mg/l				
Influent	110	52	50	35
Effluent	57	23	14	15
TSS, mg/l				
Influent	97	77	49	155
Effluent	10	6	15	14
Dissolved Oxygen, mg/l	2.3	0 Odors at night	2.1	0.5
Sampling Period	6/76-9/77	7-11/76 7-11-77 7-11/78	8/75-7/76	5/79-11/79

[a] Based on effluent flow rates.

operating depth of 1.8 m (6 ft.) comprised the aquatic system. The facility operated on secondary wastewater effluent at flow rates ranging from 1,892 cu m/day (0.5 mgd) to 3,785 cu m/day (1.0 mgd). With controlled harvesting, removals of 20 to 25 percent of the phosphorus input and 50 to 70 percent of the total nitrogen input were estimated at a detention time of 28 days (Reference 71). Increasing the detention time to 120 days reduced the incoming nitrogen values of 15 to 20 mg/l to levels as low as 0.01 mg/l with only a small effect on the efficiency of phosphorus removal.

The City of Roseville, California is the site of a pilot study determining the effectiveness of nutrient removals by a variety of aquatic macrophytes (personal communication, Dewante and Stowell Engineers, Sacramento, CA). Preliminary culture experiments tested water hyacinth, duckweed, water primrose, cattail and bullrush in 8 m (25 ft.) trenches receiving secondary wastewater effluent at varying detention times. Water hyacinths were selected for the pilot study which was initiated in 1981. Additional research includes quantifying bacterial populations associated with the aquatic plant roots.

The City of San Diego's 3,785 cu m/day (1 mgd) three year demonstration project is under design to test the feasibility of using water hyacinths for the treatment of raw sewage. The Water Utilities Department's plan could ultimately serve the City's 0.45×10^6 cu m/day (120 mgd) of sewage through a network of tanks and ponds over several hundred acres.

Full-Scale Facilities/Aquaculture Fact Sheets--

The municipal water hyacinth treatment systems listed below are considered to be experimental at the present stage of their development. These full-scale facilities are currently being monitored to learn more about system design and performance and to develop operation and management procedures.

- Coral Springs, Florida: Tertiary treatment with flows of 378 cu m/day (0.1 mgd).
- Lakeland, Florida: Advanced wastewater treatment of secondary effluent with flows of 454-977 cu m/day (0.12-0.26 mgd)
- Walt Disney World, Lake Buena Vista, Florida: Both secondary and tertiary treatment with flows of 189 cu m/day (0.05 mgd).
- Williamson Creek, Austin, Texas: Advanced secondary treatment with minimum flows of 1,325 cu m/day (0.35 mgd).

- Hornsby Bend, Austin, Texas: Secondary treatment with flows of 6,050 cu m/day (1.6 mgd).
- San Juan, Texas: Secondary treatment with flows of 1,514 cu m/day (0.4 mgd).
- Alamo, Texas: Tertiary treatment with flows of 1,514 cu m/day (0.4 mgd).
- San Benito, Texas: Advanced secondary treatment with flows of 2,460 cu m/day (0.65 mgd).
- Rio Hondo, Texas: Primary treatment with flows of 454 cu m/day (0.12 mgd).

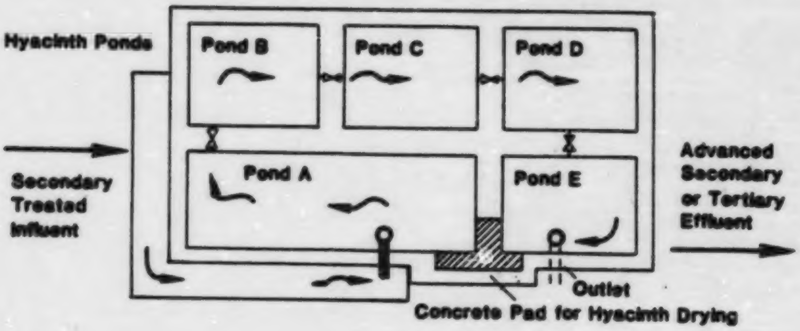
Technical descriptions, process flow diagrams, and key design and performance data for each of these systems are presented in the following fact sheets.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Coral Springs, Florida (Reference 43, 72)
OPERATED BY: Coral Springs Improvement District

DESCRIPTION: A large scale field test using water hyacinths to convert a secondary treatment plant to an advanced wastewater treatment plant has been underway since May, 1978. Based on the research by the University of Florida, the facility was designed by Gee and Jensen Engineers. Water Quality parameters of primary concern are total nitrogen and total phosphorus. Monthly data has indicated that decreasing surface loading rates resulted in increasing nutrient removal. Further investigation is underway to determine if the influent N:P ratio can be increased by ammonia addition to allow for increased phosphorus uptake.

PROCESS FLOW DIAGRAM:


Hyacinth Ponds
Pond B
Pond C
Pond D
Pond A
Pond E
Secondary Treated Influent
Advanced Secondary or Tertiary Effluent
Outlet
Concrete Pad for Hyacinth Drying

PRETREATMENT OF INFLUENT: Activated sludge.

DESIGN CRITERIA:

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day (acre/mgd)	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
Average: 379 (0.1)	Total 0.5 (1.25)	38 (1.25)	Average: 11.7 (10.8)	6	Pond A: 31	5	100

PERFORMANCE DATA:

	BOD_5 (mg/l)	TSS (mg/l)	Nitrogen (mg/l)	Phosphorus (mg/l)
Influent	13.1	5.64	22.4	11.0
Effluent	2.95	2.95	1.0	3.6
% Reduction	77	48	96	67

HARVESTING AND DISPOSAL OF BIOMASS: Periodic harvesting is necessary to prevent leaf chlorosis caused by overcrowding. Harvesting 15 to 20 percent of the plants on a four-week cycle has produced optimum results. Harvested biomass averages 137.6 cu m (180 cu yd) and after a two to three week drying period is being composted. Monthly harvesting of the hyacinths requires 6 to 7 hours and contributes the major portion of operating and maintenance costs. Harvesting equipment used consists of a weed-bucket equipped, truck-mounted guideline.

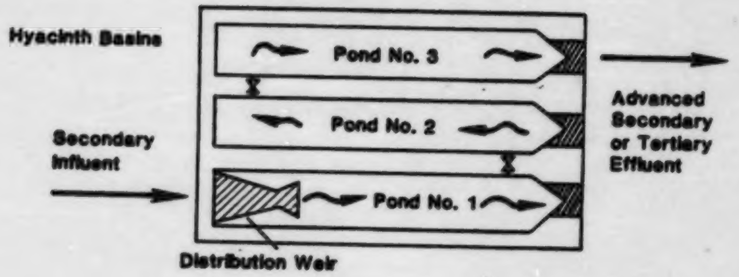
COMMENTS: Total Construction costs of the system were about $165,000.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Lakeland, Florida
OPERATED BY: City of Lakeland and Polk County, Florida (Reference 73)

DESCRIPTION: A demonstration project designed by Dawkins & Associates, Inc. was implemented in January, 1979. The capability of water hyacinths is being investigated for the removal and recovery of nutrients from secondary effluent prior to discharge. The system must meet stringent nutrient removal requirements (1.5 mg/l TN; 0.4 mg/l TP) and is further being groomed to become part of a regional facilities plan with an expansion as large as 49,200 cu m/day (13 mgd) possible. The system was designed with flexibility in manipulating depths, pollutant and hydraulic loadings, and retention times.

PROCESS FLOW DIAGRAM



DESIGN CRITERIA

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth (cm)	Surface Loading (cu m/ha/day)	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
454-977 (0.120 - 0.0258)	0.4 ha ea (1)	dna	dna	dna	dna	3	Partial

dna = data not available.

PERFORMANCE DATA

	BOD_5	TSS	Nitrogen	Phosphorus
Influent (mg/l)	8-32	4-36	6.7-27.3	3.0-5.0
Effluent (mg/l)	3-4	0-7	1.0- 4.2	1.8-3.1
% Reduction	50-90	80-100	75-85	38-40

HARVESTING AND DISPOSAL OF BIOMASS: Three harvested channels intended to accommodate a solids pump or aqua-guard self-cleaning bar screen were included as part of the design. Processing considerations of the harvested plants include chopping, pressing, and drying as part of a feed pelletizing system. Preliminary laboratory tests indicated that the pelletized feed is suitable for animal feed. The feed option and market potential will be further investigated.

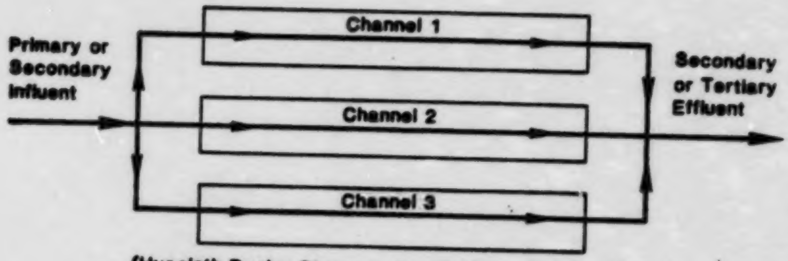
COMMENTS: Based upon the water quality and flow data and productivity rates, a nutrient and water budget for the ponds was projected for the summer study phase.

AQUACULTURE DATA SHEET

FACILITY AND LOCATION: Walt Disney World, Florida (Reference 74, 75)
OPERATED BY: Reedy Creek Utilities Company and WED Enterprises

DESCRIPTION: The ability of water hyacinths to provide both secondary and tertiary wastewater treatment is being demonstrated by WDW's Experimental Prototype Community of Tommorrow (EPCOT). A variety of modes of operation are provided by the hydraulically inter-connected concrete channels. A preliminary operation phase was started in June, 1979, with primary effluent being pumped into the channels. Results indicated that the shallower depth of 38 cm (15 inches) was more effective. Future operations include testing the hyacinths as a tertiary system, evaluating the effect of a protective cover during winter months, and determing the amount of energy consumed in the system.

PROCESS FLOW DIAGRAM



(Hyacinth Basins Shown in Parallel Flow System Mode)

DESIGN CRITERIA

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
189 (0.05)	0.1 (0.25)	Varies 38,61,91 (1.2,2,3)	dna	5-14	dna	3	100

dna = data not available.

PERFORMANCE DATA:

	July - August, 1979		September 1979-April 1980	
	BOD_5	TSS	BOD_5	TSS
Influent (mg/l)	300	200	dna	dna
Effluent (mg/l)	27.9	22.9	dna	dna
% Reduction	91	89	85	82

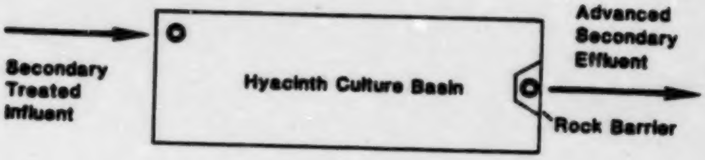
HARVESTING AND DISPOSAL OF BIOMASS: Results have indicated that the constant removal of older plants was more effective for treating wastewater. So far, maximum productivity recorded was 162 dry metric ton/ha/year. This productivity was recorded during the second week in March, 1980. The harvesting pattern for maximum productivity has not yet been determined. Harvesting equipment includes a front end loader, double-belt conveyor chopper and a forage wagon. The harvested biomass is composted utilizing a windrow-system. Extensive studies are funded for the bioconversion of water hyacinths and sewage sludge to methane gas by anaerobic digestion.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Williamson Creek Facility, Austin, Texas (Reference 41)
OPERATED BY: City of Austin

DESCRIPTION: Following the successful conclusion of the pilot studies, as discussed in the previous section, a full-scale system was placed into operation in October, 1977. A stabilization pond was converted into a hyacinth basin and is being operated as an integral unit of the facility to upgrade the secondary effluent.

PROCESS FLOW DIAGRAM



PRETREATMENT OF INFLUENT: Aeration basin, clarifer, two lagoons in series.

DESIGN CRITERIA

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
1325-1703 (0.35-0.45)	12 (3)	70-130 (2.3-4.3)	dna	6-9	56-72	1	100

dna = data not available

PERFORMANCE DATA:

(Unpublished Data)	October 1977-August 1979			September 1979-November 1980		
	BOD_5 mg/l	TSS mg/l	Fecal Coliform #/100 ml	BOD_5 mg/l	TSS mg/l	Fecal Coliform #/100 ml
Influent	41.9	40	5388	20.2	34.2	13,089
Effluent	12	8.8	302	6.6	9.1	132
Percent Reduction	71	78	--	67	73	--

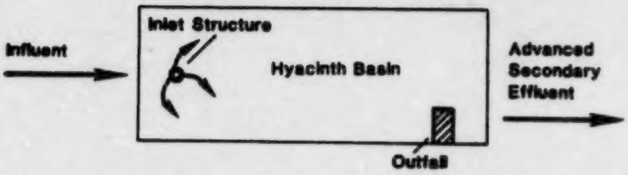
HARVESTING AND DISPOSAL OF BIOMASS: A single, annual harvest is being practiced in this system during the winter to remove dried plants and basin debris from the culture basin. Dinges suggested that continuous harvesting in small hyacinth secondary treatment systems would disrupt treatment (Reference 41). The hyacinth basin was out of operation during the winter periods as plants were frozen and in a state of decay.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Hornsby-Bend Sludge Treatment Facility, Austin, Texas (Reference 41)
OPERATED BY: City of Austin

DESCRIPTION: Waste activated sludge from two wastewater treatment plants is transferred to the Hornsby-Bend sludge pond System. A hyacinth culture basin was provided to treat the pond system overflow in May, 1979. An expansion of the hyacinth system has been approved through EPA's construction grants program. Projected plans include providing protective greenhouse covers for the hyacinth basins (personal communication with Ray Dinges, Texas Department of Health).

PROCESS FLOW DIAGRAM



PRETREATMENT OF INFLUENT: Influent is the supernatant from ponds holding waste activated sludge.

DESIGN CRITERIA

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
3937 (1.04)	1.4 (3.5)	Average 123 (4)	dna	Approx. 3	dna	1	dna

dna = data not available

PERFORMANCE DATA:

	(Unpublished Data) October 1979 - September 1980 BOD$_5$ mg/l	TSS mg/l
Influent	51.2	96
Effluent	28.9	43.7
% Reduction	45	53

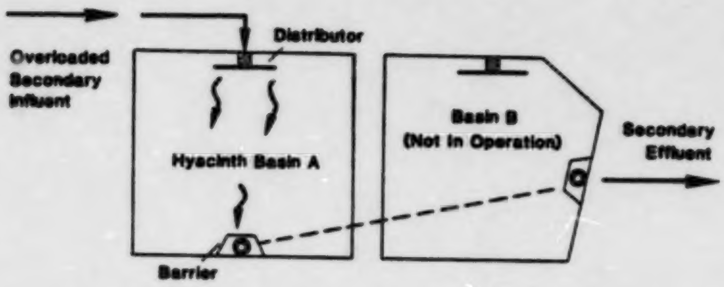
HARVESTING AND DISPOSAL OF BIOMASS: A single, annual harvest to remove dried plants and basin debris from the culture basin has been followed.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: San Juan, Texas (Reference 41)
OPERATED BY: Rio Grande Valley Pollution Control Authority

DESCRIPTION: Two hyacinth culture basins were added to the San Juan treatment facility to assist the overloaded stabilization pond system. In addition, during short periods, canning operations load the ponds at 20 times the amount that is recommended. Basin A has been in operation and tested at various depths and flow rates since July, 1978.

PROCESS FLOW DIAGRAM



PRETREATMENT OF INFLUENT: Aerated lagoon, stabilization pond.

DESIGN CRITERIA

Flow cu m/day (mgd)	Area ha (acre)	Basin Depth cm (ft)	Hydraulic Surface Loading cu m/ha/day	Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
a. 870 (0.23)	each pond is 0.1 (2.5)	61 (2)	dna	7	dna	2	dna
b. 852 (0.22)		91 (3)		11			
c. 1552 (0.41)		91 (3)		6			
d. 1855 (0.49)		137 (4.5)		7			

dna = data not available

PERFORMANCE DATA:

	Test Results for July-May 1979 for Basin A						
	Influent	Effluent	% Reduction		Influent	Effluent	% Reduction
BOD_5 mg/l	a. 90	20	78	TSS mg/l	a. 111	30	73
	b. 86	9	89		b. 113	11	90
	c. 266	35	87		c. 222	30	86
	d. 319	31	90		d. 282	32	88

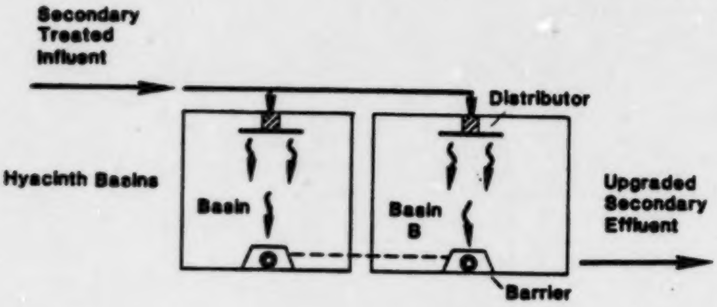
HARVESTING AND DISPOSAL OF BIOMASS: A single annual harvest to remove dried plants and basin debris from the culture basin has been followed.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Alamo, Texas (Reference 41)
OPERATED BY: Rio Grande Valley Pollution Control Authority

DESCRIPTION: Two hyacinth culture basins were completed and planted with hyacinths in April, 1979. The basins were placed into operation to supplement the existing stabilization ponds in the treatment of domestic effluent and cannery wastes.

PROCESS FLOW DIAGRAM


Secondary Treated Influent
Distributor
Hyacinth Basins
Basin
Basin B
Upgraded Secondary Effluent
Barrier

PRETREATMENT OF INFLUENT: Imhoff tank, trickling filter, aeration basin, two stabilization ponds in parallel.

DESIGN CRITERIA:

(Note: Limited preliminary data)

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
dna	1.35 (3.3) 1.05 (2.6)	dna	dna	dna	dna	2	dna

dna=data not available

PERFORMANCE DATA: Data not available.

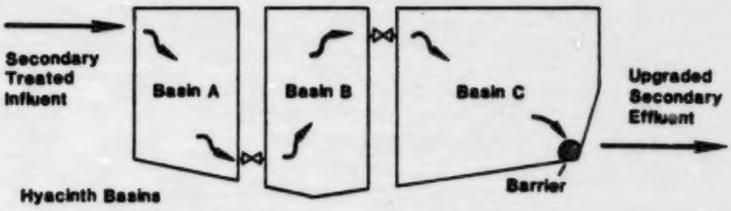
HARVESTING AND DISPOSAL OF BIOMASS: Data not available.

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: San Benito, Texas (Reference 41)
OPERATED BY: City of San Benito

DESCRIPTION: The last pond in a stabilization pond system was divided into three sections by earthen dikes to serve as an experimental hyacinth treatment facility.

PROCESS FLOW DIAGRAM



PRETREATMENT OF INFLUENT: Four stabilization ponds in series.

DESIGN CRITERIA:

Flow cu m/day (mgd)	Surface Area ha (acre)	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
	A. 0.8 (2)						0
dna	B. 0.8 (2)	dna	dna	dna	dna	3	50
	C. 2.0 (5)						100

dna = data not available

PERFORMANCE DATA:

	April 1978-March 1979 BOD$_5$	April 1978-March 1979 TSS
Influent	dna	dna
Effluent (mg/l)	17	35

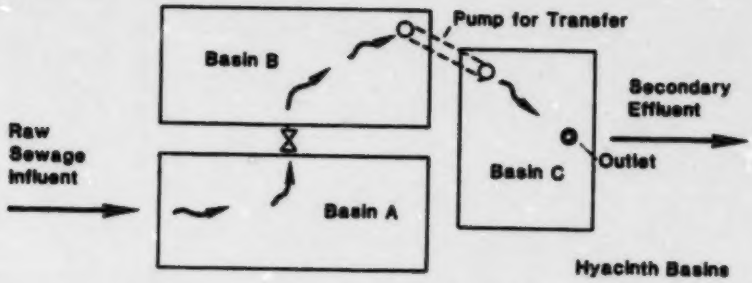
HARVESTING AND DISPOSAL OF BIOMASS: Changes in the design and operation of the system are being considered after termination of the experimental phase. Considerations include large circular concrete hyacinth basins divided into "pie-shaped" sections (personal communication with Ray Dinges, Texas Department of Health).

AQUACULTURE FACT SHEET

FACILITY AND LOCATION: Rio Hondo, Texas (Reference 41)
OPERATED BY: The City of Rio Hondo

DESCRIPTION: The City of Rio Hondo planted hyacinths in their raw sewage stabilization pond a few years ago. Pond effluent quality improvement was noted but was hampered by the sludge deposition accumulating since 1950. The stabilization pond was bypassed in 1978 and raw wastewater discharged directly into constructed hyacinth culture basins.

PROCESS FLOW DIAGRAM



PRETREATMENT OF INFLUENT: None

DESIGN CRITERIA:

Flow cu m/day (mgd)	Surface Area ha (acre	Basin Depth cm (ft)	Surface Loading cu m/ha/day	Hydraulic Detention Time (days)	Organic Loading (kg/ha/day)	Number of Basins	Percent Plant Cover
454 (0.12)	0.41 ea (1)	dna	dna	dna	For Basin A: 197	3	100

dna = data not available

PERFORMANCE DATA:

	July 1978-May 1979		June 1979-March 1980*	
	BOD_5	TSS	BOD_5	TSS
Influent	dna	dna	dna	dna
Effluent (mg/l)	16	24	17	18

*Unpublished data

HARVESTING AND DISPOSAL OF BIOMASS: There has been some periodic removal of dried plants with a dragline.

COMMENTS: The city has recently restored the raw sewage stabilization pond and placed it back into operation. Modifications were also made to improve the distribution of wastewater through hyacinth basins (personal communication with Ray Dinges).

Invertebrates

Bench Scale Research--

An experimental system was designed for the controlled eutrophication of wastewaters with a marine algae (*Tetraselmis*) and brine shrimp (References 78 and 79). In a series of batch laboratory tests, *Tetraselmis* was cultured in the first stage in beakers containing various dilutions of raw and treated wastewaters to use as a food source for brine shrimp (second stage) while water quality parameters were monitored. Results from this two-stage process indicated that there was a substantial drop in total suspended solids and ammonia, little change in phosphates, nitrates and nitrites, and an increase, in all cases, in BOD during the 72-hour test periods. An algae stage was added after the brine shrimp to allow for further reduction of the BOD values. Results from the three-stage process (raw wastewater algae brine shrimp algae) employing 250-ml containers under batch conditions are summarized in Table 10. The experiment allowed for 24-hours growth for each of the algae steps and 48 hours for brine shrimp.

TABLE 10. SUMMARY OF WATER QUALITY PARAMETERS RESULTING FROM A THREE-STAGE BATCH LABORATORY EXPERIMENT CULTURING A MARINE ALGAE (*TETRASELMIS*) AND BRINE SHRIMP FOR 96 HOURS (References 78 and 79)

Parameter (mg/l)	Influent (raw wastewater)	Stage 1 (algae culture)	Stage 2 (brine shrimp culture)	Stage 3 (algae culture)	% Reduction (influent to Stage 3)
BOD_5	318.0	5.5	23.0	4.5	98
TSS	120.0	45.0	20.0	3.5	97
NO^-_3	30.0	14.5	7.0	1.0	97
NO^-_2	0.02	0.01	0	0	100
NH_3	0.30	0.10	0.75	0.02	93
PO_4^{3-}	20	16.5	10.0	4.8	76
pH	7.0	8.8	8.7	8.7	—

A continuous flow system was incorporated into the laboratory experiment to study the retention and survival of pathogenic bacteria and viruses. A significant reduction in the number of fecal coliforms and enterococci on the passage of raw sewage through the algae and brine shrimp culture tanks was reported. No enterococci and an insignificant number of coliforms (3.7 per brine shrimp) were isolated from tissue specimens, which were assumed to be associated with the algae present in the gut of the brine shrimp.

Pilot Scale Research--

An experimental pilot pond, provided by the City of Giddings, Texas, and supplied with a portion of effluent from a waste stabilization pond, was used to maintain a Daphnia (water flea) culture under controlled conditions to upgrade secondary effluent (References 80 and 81). Severe restrictions of Daphnia production in most pond systems are related to high pH levels due to algae growth. Preliminary studies evaluated the effectiveness of pH control by regulation of pond exposure to sunlight, chemical addition, and sulfide reduction through mixing-aeration of pond waters. Sustained culture of Daphnia at a high population level was found to be feasible. Water quality parameters evaluated during two study phases of the Daphnia culture unit are summarized in Table 11. Detention time for both study phases was 11 days with a BOD_5 loading rate of 39 to 49 kg BOD_5/ha/day (35 to 44 lbs. BOD_5/acre/day).

TABLE 11. SUMMARY OF WATER QUALITY PARAMETERS AFFECTED BY A DAPHNIA CULTURE POND DURING A CONTROLLED OPERATION PERIOD (References 80 and 81)

	First Study Phase January 1972 - March 1972			Second Study Phase February 1973 - April 1973		
Parameter	Influent	Effluent	Percent Reduction	Influent	Effluent	Percent Reduction
BOD_5, mg/l	45.4	14.2	69	57.5	11.8	79
COD, mg/l	271.1	90.6	67	158.5	70.0	55
VSS, mg/l	77.2	10.8	86	78.4	13.0	83
Total Coliforms, per 100 ml	32,680	9,160	72	—	—	—
Fecal Coliforms, per 100 ml	6,880	84	99	—	—	—

Utilization of soluble nutrients and minerals were limited in the Daphnia culture unit. Phosphorus content of the effluent was comparable to that of the influent. Nitrate and organic-bound iron accumulated in the unit. Daphnia harvest and potential usage as a protein additive to animal feeds was considered. Based on experiences gained from the pilot pond operation, Dinges formulated zooplankton culture unit design and operating features (Reference 82).

A similar two-stage Daphnia culture unit also designed to upgrade secondary effluent was explored by the Las Virgenes Municipal Water District, California, in 1973 (Reference 83). The system consisted of a shallow algae culture pond followed by a Daphnia culture pond. The system's reduction of COD was reported to be above 40 percent. Nitrogen and phosphorus removal efficiencies were hampered by occasional invasion of Daphnia in the first-stage pond, which decimated the algal population. Lack of success in controlling such events was the principal obstacle to further development of the pilot system (Reference 15).

Fish

General Studies--

Numerous examples of fish culture operations with a variety of species in wastewater stabilization ponds are noted in the literature (Reference 84). In 1969, channel catfish were stocked and raised successfully in a series of four tertiary sewage treatment ponds located in Ames, Iowa (Reference 85). The following year, fathead minnows were propagated in the same ponds (Reference 86). The same fathead minnow propagation in a municipal wastewater stabilization pond was demonstrated by Trimberger in Michigan (Reference 87). Recently, an investigation was conducted in Wisconsin to assess the potential of wastewater treatment lagoons located in that state as culture sites for fathead minnows (Reference 88). The feasibility of developing a sport fishery in tertiary treated wastewater was tested with channel catfish, Tilapia hybrids, and rainbow trout (Salmo gairdneri) at the Tucson Sewage Treatment Plant, Arizona (Reference 89). Although certain water quality parameters, including dissolved oxygen, ammonia, orthophosphate, BOD, turbidity and water temperature, were considered and monitored during these operations, analysis of water quality improvement was limited as these systems were orientated toward examining the suitability of lagoon effluents for fish production.

A lagoon wastewater treatment system was used for rearing muskellunge (Esox masquinongy) to 23 to 25cm (9 to 10 in.) lake planting size in Dorcester, Wisconsin (Reference 90). The system consisted of two aerated lagoons, each 0.57 ha (1.4 acre), with an average depth of 3m (10 ft.). Minnows and 5,000 - 6cm (2.5 in.) long muskie fingerlings were stocked in the following third pond, 0.2 ha (0.5 acre) and 3 m (10 ft) in depth.

At a flow of 241 cu m/day (63,600 gpd) and loading rate of 101 kg BOD_5/day (22 lb BOD_5/day), detention times averaged 51 days for each of the first two lagoons and 26 days for the fish culture unit. Monthly effluent quality data recorded from January, 1976, to December, 1977 averaged about 6 mg/l for both BOD_5 and suspended solids and did not exceed 16 mg/l during the entire test period. Data for the fish culture unit alone was not available, thus the extent to which the fish contributed to the effluent quality improvement is not known. However, experience with other aerated lagoon systems of this type suggests that the fish culture pond may have served as a polishing unit reducing BOD values and suspended solids in the final effluent (Reference 15).

Pilot Scale Research--

Two pilot studies which evaluated the effect of fin fish on water quality improvement were conducted by Coleman et al. (References 40 and 91) at the Quail Creek Lagoon System in Oklahoma City (1973) and by Henderson at the Benton Services Center, Arkansas (1978-79) (Reference 39). Both studies utilized six-cell (operated in series) lagoon systems to treat raw wastewater. The first two cells were for wastewater stabilization and plankton culture and the remaining four used for the polyculture of fish. The Quail Creek system used mechanical aeration for the initial stabilization step and channel catfish as the major culture species. The system in Arkansas accomplished initial wastewater stabilization without supplemental aeration and used silver and bighead carp as the major culture species. The design characteristics and performance data for the last four cells of these two fish systems are summarized in Table 12. All parameters are based on the fish culture unit only.

Both systems performed satisfactorily in removing organics and suspended solids and provided an advanced secondary effluent. The secondary treatment standard for BOD_5 of 30 mg/l was met in the effluent from the second cell in the Quail Creek System. The secondary standards for suspended solids (30 mg/l) and fecal coliform (200/100 ml) were met in the effluent from the fifth cell. In the Arkansas System, BOD_5 and suspended solids standards were met in the effluent of the first fish cell. There were no reported incidents of fish kills, indicating that the ammonia, nitrate, dissolved oxygen, and pH levels (shown in Table 12) were within tolerable ranges for the cultured fish species. As no supplemental feeding of fishes occurred during both experiments, increase in fish biomass was dependent upon constituents present within the system. A food habits study by Coleman et al. allowed general classification of the fishes according to position in the food web.

TABLE 12. SUMMARY OF DESIGN CHARACTERISTICS AND PERFORMANCE DATA FOR TWO PILOT STUDIES UTILIZING FISH FOR WASTEWATER TREATMENT (Reference 39, 40, 91)

	Design Criteria	
Item	Quail Creek Plant Oklahoma	Benton Services Center Arkansas
Method of influent stabilization	Mechanical aeration	Unaerated stabilization ponds
Sampling period	6-73 to 10-73	12-78 to 7-79
Major fishes cultured	Channel catfish	Silver and Bighead Carp
Minor fishes cultured	Tilapia Minnows	Channel catfish Buffalofish Grass carp
Flow, cu m/day	3785 (1.0 mgd)	1,711 (0.45 mgd)
Surface area, ha	64 (26 acres)	6.5 (16 acres)
Depth, m	3-3.6 (10-12 ft.)	1.25 (4 ft.)
Detention time, days	Not available	48
Organic loading rate	Not available	
kg BOD_5/ha/day		43.5 (38.8 lb/ac/day)
kg TSS/ha/day		20.4 (18.2 lb/ac/day)
Initial fish stocked kg/ha	29 (26 lb/acre)	426 (380 lb/acre)
Net fish production kg/ha/mo	44 (39 lb/acre/mo)	417 (390 lb/acre/mo)

	Performance Data					
	Oklahoma			Arkansas		
Wastewater Parameter	Influent*	Effluent**	% Reduction	Influent*	Effluent**	% Reduction
BOD_5, mg/l	24	6	75	28.1	9.4	67
TSS, mg/l	71	12	83	38.0	17.1	55
Total N, mg/l	7.04	2.74	61	—	—	—
NH_3-N, mg/l	0.4	0.12	70	5.1	2.0	60
NO_2-N, mg/l	0.96	0.16	83	0.02	0.11	Negative
NO_3-N, mg/l	2.31	0.29	87	0.01	0.5	Negative
Total P, mg/l	7.95	2.11	74	3.0	2.5	17
Fecal coliform, No/100 ml	1380	20	—	—	—	—
pH	8.2	8.3	—	7.9	8.2	—
DO, mg/l	—	—	—	3.0	7.4	—

*effluent from cell 2
**effluent from cell 4

Analysis to determine levels of human pathogenic microorganisms present in the wastewater and cultured fish were performed for both systems. Results of a bacteriological study at Quail Creek showed a reduction of fecal coliform bacteria to less than detectable levels. No pathogenic bacteria were found in the wastewater beyond the first two conventional cells, nor in any of the cells containing fish, or in any of the fish sampled. Levels of pesticides, heavy metals, and pathogenic bacteria present in influent wastewater, wastewater from the fish ponds, and fish flesh were determined in the Arkansas system. With the exception of the metals copper and mercury, and staphylococcus bacteria, all samples showed less than the standard detection limits or were negative.

The same system in Oklahoma was operated the following year without stocking fish in the final lagoons for a follow-up comparison study. Coleman noted that a significantly higher quality effluent resulted with fish present in the system and that the suspended solids effluent criterion was not met without the fish. A preliminary study in 1975 at the Benton site also compared effluent quality from ponds stocked with and without fish. The flow pattern in the study was arranged so there were two completely independent three-pond series, each receiving half of the total volume. Silver and bighead carp were stocked in one series. Notable differences in effluent quality were found in the types of phytoplankton organisms present and BOD_5; the effluent without fish was 37.6 percent higher in BOD_5 than in the series containing the fish.

On a global basis, fish ponds for sewage purification have been widespread (References 84 and 92), and a classic example is the famous sewage fish ponds operated by the Bavarian Power Company at Munich, Germany, for the production of common carp to sell for human consumption (References 1 and 93). This fishery was established in 1929, and for many years provided final treatment of the pre-settled sewage from the entire city. The present operation treats only one-third of the city's sewage. The complex consists of a 7 km (4.35-mile) chain of 30 ponds ranging in size from 4 to 10 ha (11 to 25 acres), and containing a total area of about 245 ha (600 acres). The ponds are stocked with common carp of 0.3 kg (0.66 lb.) initial weight at a rate of 500 per ha (200/acre), and are operated over a six-month growing season. Throughout the growing season, effluent from the settling tank is diluted with river water at a ratio of 1:3 to 1:6 and fed continuously into the fish ponds. Retention time in the fish ponds is only about 1.5 days. The BOD_5 is reduced from 60 mg/l in the original pre-settled wastewater to the range of 2 to 6 mg/l when it leaves the fish ponds after dilution. The rate of fish growth is about 500 kg/ha (450 lbs/acre) of fish flesh without supplemental feeding. The cost of the installation has long been amortized, and the annual net profit from the sale of fish was estimated at $12,500 in 1970. The entire operation is conducted by only three staff personnel, providing a yield of over 27,210 kg (30 tons) of fish flesh per man year of labor.

Integrated Systems

General Studies--

The performance of a five-step biological treatment system receiving stabilization pond effluent was evaluated by Dinges to test the feasibility of an integrated system using controlled cultures of higher aquatic plants and animals (Reference 81). The system consisted of a pH reduction filter (a novel biological filter intended to reduce the influent pH to permit zooplankton growth) and a culture unit, 85m (280 ft.) in length, 90m (30 ft.) in width, and 0.6m (2 ft.) in depth, divided into four sections by rock barriers. The first pond, approximately one-half of the culture unit, contained water hyacinths, snails, and insects. The second pond cultured zooplankton and was covered with duckweeds to restrict algae growth. A portion of the second pond was 2.4m (8 ft.) in depth and aerated by using an airlift pump. Shrimp and fish were stocked in the third and fourth ponds, respectively, to feed on the zooplankton growth and algae regrowth. Theoretical retention time for the system was 5.3 days. Results for a five-month period of operation are summarized in Table 13. Loading rates per unit surface area were calculated by Schwartz (Reference 15) and based on $118 m^3$/day (31,336 gpd) flow.

TABLE 13. PERFORMANCE OF A FIVE-STEP INTEGRATED TREATMENT SYSTEM FROM JUNE TO NOVEMBER, 1975 (References 15 and 81)

Wastewater Parameter	Organic Loading Rate[a] kg/ha/day (lb/acre/day)	Influent mg/l	Effluent mg/l	Percent Reductions
BOD_3	22.7 (20.3)	15	3.5	77
BOD_{20}	136.6 (122.0)	90	18	76
COD	106.3 (95.0)	70	40	43
TSS	53.1 (47.4)	35	7	80
Total Organic Nitrogen	—	4.8	1.2	75
Ammonia	—	2.1	0.1	95
Fecal coliform/100 ml	—	1400	10	—

[a] Calculated based on 118 cu m/day (31,336 gpd) flow.

After the initial study period, the system was modified into a water hyacinth culture basin as the scheme did not function as anticipated (Reference 65). An inadequate food supply to support zooplankton production resulted in poor survival of the stocked animals which feed on the zooplankton.

Extensive research was conducted at the Environmental Systems Laboratory of the Woods Hole Oceanographic Institute on a pilot-scale, integrated tertiary wastewater treatment-marine aquaculture system (References 94, 95, 96, and 97). Primary objectives of the research were to develop a process capable of removing all of the inorganic nitrogen from secondary wastewater effluent prior to discharge, while culturing commercially valuable marine organisms. The system was composed of continuous flow-through ponds for the culture of marine phytoplankton and raceways for the culture of shellfish and seaweeds. Secondary commercial crops of marine animals, American lobster, and flounder were stocked in the shellfish raceways to feed on shellfish wastes and dense populations of small invertebrates.

Secondary wastewater effluent, mixed with seawater at various proportions, was used as the source of nutrients to culture single-cell marine algae in shallow ponds (132 cu m, 35,000 gallons). The maximum algal production on an ash-free dry weight basis was estimated at 12 g/sq m/day, with a nitrogen removal rate of 1.2 g/cu m/day. Based on mean nitrogen removal rates of 3 kg/ha/day (2.7 lbs/acre/day) during the winter and 8 kg/ha/day (7.1 lbs/acre/day) during the summer, Ryther projected the area requirement for the algae pond at 82 sq m/cu m flow/day (77 acres/mgd) in the winter, and 28 sq m/cu m flow/day (26 acres/mgd) in the summer for secondary effluent with a nitrogen content of 24 mg/l. Algal production was periodically inhibited by dissolved and particulate organic matter in the secondary effluent, temperature variations, and protozoan predation.

Harvest from the algal cultures, diluted with 1 to 5 parts of seawater, was fed into concrete raceways, 12 m by 1.2 m and 1.5 m in depth (40 x 4 x 5 feet), containing stacked trays of bivalve mollusks. Initial attempts at shellfish culture using American oysters (Crassostrea virginica) and hard clams (Mercenaria mercenaria) met with little success due to slow growth rates and high mortalities. The predominate growth of the algae species of Phaeodactylum tricornutum in the eutrophic algae cultures was inferior and unsuitable as food for the shellfish. Inability to control the algal species was overcome by use of exotic shellfish species capable of utilizing the kinds of algae that could be mass produced. They included the Manila clam (Tapes japonica), European oysters (Ostrea edulis) and Japanese oysters (Crassostrea gigus). Related smaller scale studies compared the growth of these bivalve mollusks, along with the mussel (*Mytilus edulis*), in wastewater-enriched cultures (Reference 98 and 99). Throughout the pilot-scale study, bivalve mollusks were sampled at monthly intervals and assayed for trace metals (Reference 100). Shellfish trace metal contents were consistently below FDA alert levels.

Effluent from the shellfish cultures was passed through a culture of seaweeds, grown in suspended cultures in raceways having the same dimensions as the shellfish raceways. This served as a final polishing step, prior to discharge, removing nutrients not initially assimilated by the phytoplankton and those excreted by the shellfish. After initial experimentation with several seaweed species, research was concentrated on two red algae of potential commercial value.

Results obtained from the operation of the seaweed growth unit were so favorable that the following year experiments were initiated in which seaweeds were grown alone, in a single-step waste recycling system. The maximum production of the seaweed (*Gradilaria tikvahiae*) on an ash-free dry weight basis was estimated at $16g/m^2/day$, with a nitrogen removal rate of $0.6g/m^3/day$.

The mass balance for inorganic nitrogen for the entire Woods Hole system was determined during a steady-state operation period. Total nitorgen removal efficiency including the seawater input and output was 89.3 percent. When nitrogen values for the seawater were subtracted, the nitrogen removal efficiency was 93.6 percent.

AVAILABLE EQUIPMENT/HARDWARE

Removal and recycling of the nutrients and components in a wastewater aquaculture system are completed by harvesting, processing, and utilizing the aquatic species in which the nutrients are collected.

An efficient harvesting system is a necessary requirement for a large scale aquatic plant system and/or a system designed for nutrient removal. Harvesting promotes healthy plant conditions, and subsequently insures optimum system peformance. Direct harvest of the plants can be manual or mechanical, depending upon the size of the system and the level of local technology. Many different methods of harvesting water hyacinths have been tried with varying degrees of success (References 102 through 103). Research by Wolverton comparing several types of harvesting equipment indicated that the best performance could be obtained using a modified clamshell bucket (Reference 35). Results were based on harvesting efficiencies as evaluated in terms of surface area harvested per hour.

Types of equipment used for hyacinth harvesting include truck mounted draglines, front-end loaders and backhoes equipped with clamshell buckets, weed buckets or other specially designed buckets, single-wide and double-belt conveyors, self-cleaning bar screens, and solids pumps. Available equipment can be modified to facilitate harvesting with the addition of a suitable bucket, chopper or rake. Boats, over-head reels, and rakes are used to push the plants toward the harvester. Duckweeds have been harvested by means of a continuous in-line effluent skimming device followed by static screening (Reference 102). Equipment selected for harvesting should be mobile to allow for the removal of plants from all portions of the system. Dump trucks, forage wagons, and small tractors can transfer the harvested biomass to a reuse area.

Plant material harvested from the system is usually processed to reduce moisture content. This in turn reduces the volume of plant biomass and aids in biomass disposal. Processing is also a necessary percursor to all of the viable and potential hyacinth produces with the possible exception of the soil amendment products. Processing may include chopping, pressing, grinding, or drying. Harvested plants can be chopped with crimpers, agricultural flail or cylinder shear bar choppers, or fluid choppers. Incorporating the harvesting and chopping mechanisms into a single machine has been recommended (Reference 103). Most of the current research has involved continuous flow screwpresses, screen presses, and belt filter presses. Pressed or pre-wilted hyacinths can be dried in forage, rotary, or solar driers.

Alternative water hyacinth processes and products are shown in Figure 4. The simplest disposal or reuse method for hyacinths, and the one presently employed by most of the full-scale facilities, is use as a soil amendment. Intact or chopped hyacinths, fresh or composted, have been applied to the soil as a source of fertilizer and mulch.

Harvesting techniques for animal-based systems are not well developed and ultimate utilization or disposal of the harvested biomass has not been given much attention.

Conventional surface and submerged aerators have been employed in several of the water hyacinth and duckweed systems. An aeration system consisting of submerged air diffusers was incorporated into the design of a full-scale aquatic plant system (Reference 104) and an experimental fish system (Reference 65).

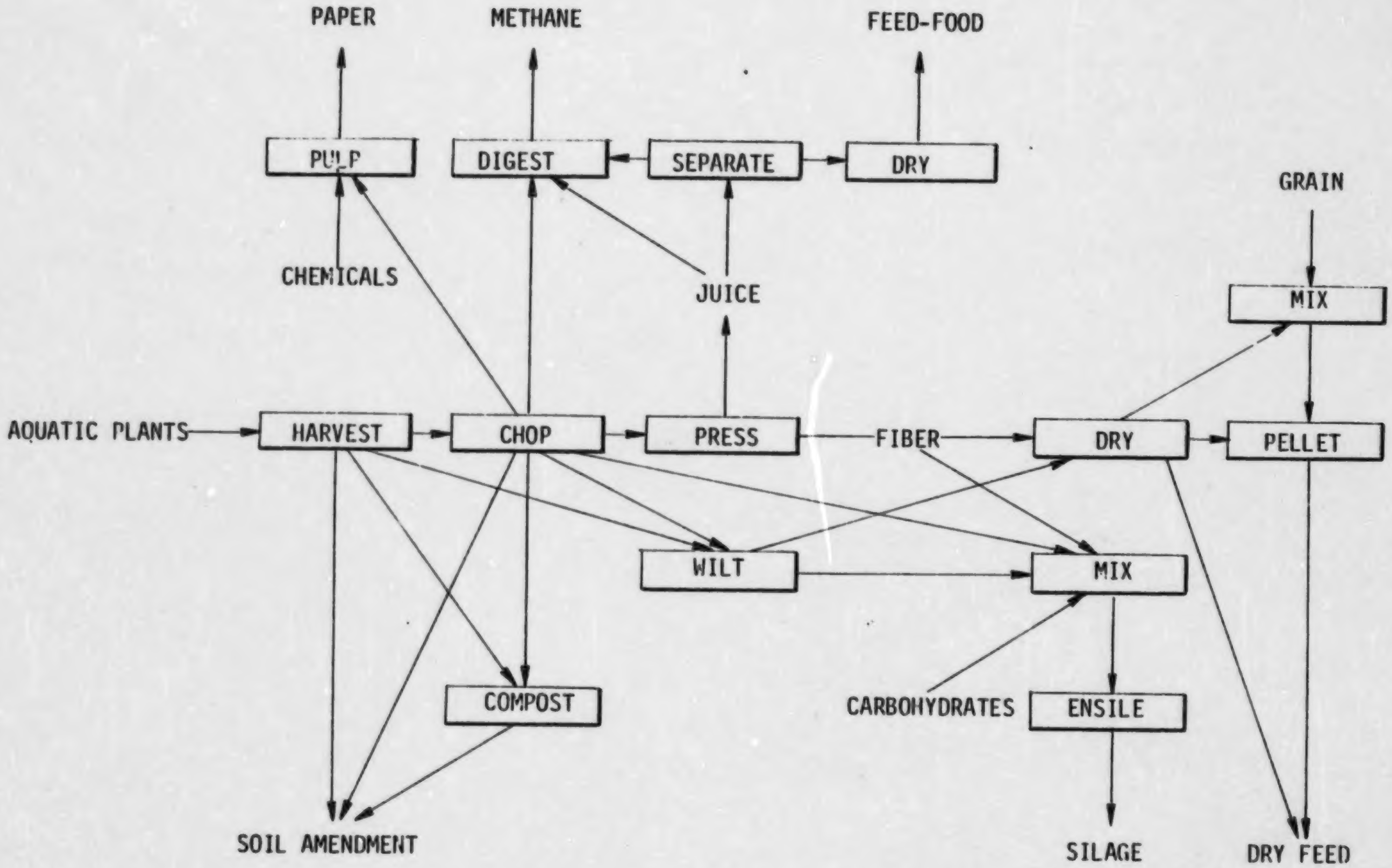

PAPER
METHANE
FEED-FOOD
PULP
DIGEST
SEPARATE
DRY
GRAIN
CHEMICALS
JUICE
MIX
AQUATIC PLANTS
HARVEST
CHOP
PRESS
FIBER
DRY
PELLET
WILT
MIX
COMPOST
CARBOHYDRATES
ENSILE
SOIL AMENDMENT
SILAGE
DRY FEED

FIGURE 4. A network of possible water hyacinth processes and products. (reference 103).

The following includes a list of names and addresses of manufacturers of such equipment. It must be noted that harvesting and processing equipment are still being researched and developed for use in full-scale aquatic plant wastewater treatment systems. Therefore, this list cannot be considered complete. Also, standard harvesting, processing, and wastewater equipment may be modified to accommodate for the system design.

HARVESTING EQUIPMENT

Aquamarine Corporation
225 North Grand Avenue
P.O. Box 616
Waukesha, WI 53187
414/547-0211

COMPOSTING EQUIPMENT

Resource Conversion Systems, Inc.
9039 Katy Freeway, Suite 300
Houston, TX 77024
713/461-9228

AERATION EQUIPMENT

Hinde Engineering Company
654 Deerfield Road
P.O. Box 188
Highland Park, IL 60035
312/432-6031

Wyss, Inc.
2493 CR 65
Rt. 1
Ada, Ohio 45810
419/634-1971

PROCESSING EQUIPMENT

Aeroglide Corporation
7100 Hillsborough Road
Raleigh, NC 27611
919/851-2000

Volusia Tool, Inc.
P.O. Box 904
Lake Helen, FL 32744
904/228-2828

Passavant Corporation
P.O. Box 2503
Birmingham, AL 35201
205/853-6290

Vincent Processors Company
1825 Grant Avenue
Tampa, FL
813/247-6324

R. A. Litkenhaus &
Assoc., Inc.
P.O. Box 16323
Jacksonville, FL 32216
904/737-3536

SECTION 4

TECHNOLOGY EVALUATION

PROCESS CONCEPT

Aquatic Plant Systems

The treatment mechanisms operative in aquatic plant systems are functions of the existing physical conditions, the biological habitat resulting from the environment provided by the plants, and the removal of soluble substances from the water by plant growth (Reference 65). When aquatic plants, particularly water hyacinths, assume a primary role in a wastewater lagoon, the operation of the system is significantly altered (Reference 68). The algae community is replaced by rapidly growing macrophytes that convert dissolved organics and nutrients into a standing biomass which is not rapidly recycled. The hyacinth plant biomass, which remains with the system, is not present in the effluent.

The culture of aquatic plants in a shallow basin filled with wastewater results in a unique ecosystem (Reference 65). The canopy formed by the growth of plant leaves shades the water surface and minimizes mixing of basin waters by wind action. The shading also moderates water temperature fluctuations. The pH level in waters beneath a hyacinth mat remains neutral. Surface basin waters contain low levels of dissolved oxygen and bottom waters and sediment are anoxic.

The extensive, fibrous root system of floating macrophytes extending down into the wastewater provides surface area and a suitable substrate for a very active mass of organisms which assist in the treatment. Bacteria, fungi, predators, filter feeders and detritovores have been reported present in large numbers living on and among the plant roots. The biological reduction, oxidation and consumption processes performed by this complex community in a plant culture basin serve to stabilize the water by releasing stored potential energy (Reference 41).

Removal of suspended solids in plant covered lagoons is accomplished by the natural processes of filtration and sedimentation which is enhanced in the still waters.

Filtration is accomplished by the root systems of the plants, which physically entrap suspended solids and which are mechanically removed from the wastewater during harvesting. Horizontal movement of suspended solids in a basin is inhibited by the plant roots. This has been illustrated in several water hyacinth systems in which plant roots growing in the vicinity of the inlet became covered by an algae slime from incoming algae cells (Reference 65).

An effective way of reducing suspended solids in lagoon effluents is by reducing population by allowing almost complete coverage of the basin with aquatic plants, the plant leaves shade the water surface and limit algae growth.

The formation of the sludge-like biomass on plant root systems also aids in BOD removal. Soluble BOD is removed by the process of adsorption and incorporation into bacterial cell mass while nitrogenous BOD is specifically removed by the plant's utilization of nutrients. The removal rate is dependent on root absorption and plant metabolic functions in combination with natural biochemical and physical treatment mechanisms.

In an aquatic plant system, during the active growth phase, plants are capable of absorbing soluble organics, heavy metals, pesticides, and other contaminants. Nitrogen, phosphorus, potassium, sulfur, calcium, and other minerals are incorporated into the plant tissues and can be removed from the wastewaters to some desirable degree by harvesting the plant biomass. Removal of nutrients, such as nitrogen and phosphorus, is dependent on plant growth and harvesting rates. Quantities of these elements essential for plant growth can be removed in proportion to their composition ratios in the plant species. Thus the composition of plants, per unit of dry matter, removed from a wastewater treatment system can provide an initial estimate of nutrient removal potential.

Nutrient removal in aquatic plant systems, however, is more complex than uptake by the plant alone. Other responsible mechanisms include physiochemical reactions and uptake by other organisms growing in the ecosystem. Substrate to support populations of nitrifying bacteria is provided in the aerobic zone of a hyacinth basin. Bottom waters and sediment provide a favorable environment for denitrifying bacteria. Some nitrogen is also incorporated into the bottom sediment. Phosphorus is principally removed from wastewater by several chemical absorption and precipitation reactions occurring primarily at the sediment layer.

Aquatic Animal Systems

The primary treatment mechanism operative in animal-based aquaculture treatment systems is the control of suspended solids. By stocking and culturing fish and/or invertebrates in wastewater treatment ponds, simple organics, algae and suspended particulates are converted into animal flesh. The control of suspended solids may be accomplished by several methods. Aquatic animals, such as phytophagous fish or bivalves, cultured in wastewaters have the ability to directly filter phytoplankton out of the water. The addition of zooplanktivorous fish to wastewater systems can reduce the zooplankton. The concept of using fishes that feed on different segments of the plant and animal community in a wastewater pond is employed in polyculture systems. A controlled ecosystem may be developed in which organisms are cultured that progressively feed on higher trophic levels.

The presence of higher aquatic animals in wastewater ponds produces a system that is more biologically balanced and in doing so increases the waste treatment capacity of that system (Reference 92). Both dissolved oxygen and pH are significantly and consistently higher in wastewater ponds stocked with fish (Reference 105). The oxygen regime is improved by fish grazing on plankton which are abundantly produced in waste-enriched waters. This grazing controls the phytoplankton blooms and eliminates the typical cycles of plankton bloom and die-off with the accompanying anaerobic or low dissolved oxygen conditions in the latter phase. Raising the dissolved oxygen increases the rate at which the BOD of the waste is satisfied.

A photosynthesis balance in a wastewater pond also eliminates excesses of dissolved carbon dioxide, which depress the pH. A higher pH is reported to increase the rate of coliforms reduction in an aquatic system (Reference 106). Increased pH also improves the effectiveness of the pond as a nutrient trap. Nitrogen is more readily lost to the atmosphere as NH_3, and phosphates become less soluble and therefore are precipitated more completely. Thus, both of the changes in dissolved oxygen and pH within an aquaculture treatment system are improvements to the operations of a wastewater pond designed to provide an effluent low in BOD, nutrients and coliform.

The principal wastewater contaminant removal mechanisms in aquaculture treatment systems are discussed in detail by Stowell et al., and are summarized in Table 14 (Reference 13). The effect of each mechanism depends on the design and management of the aquaculture system, the quality of the influent wastewater, and climatic and environmental factors.

TABLE 14. CONTAMINANT REMOVAL MECHANISMS IN WASTEWATER AQUACULTURE EMPLOYING PLANTS AND ANIMALS[a] (Reference 13)

Mechanism	Contaminant Affected[b]	Description
Physical		
Sedimentation	P - Settleable Solids S - Colloidal Solids I - BOD, Nitrogen, Phosphorus, Heavy Metals, Refractory Organics, Bacteria and Virus	Gravitational settling of solids (and constituent contaminants).
Filtration	S - Settleable Solids, Colloidal Solids	Particulates filtered mechanically as water passes through root masses substrate, fish, or invertebrates.
Adsorption	S - Colloidal Solids	Interparticle attractive force (van der Waals force).
Chemical		
Precipitation	P - Phosphorus, Heavy Metals	Formation of or co-precipitation with insoluble compounds.
Adsorption	P - Phosphorus, Heavy Metals S - Refractory Organics	Adsorption on substrate and plant surfaces
Decomposition	P - Refractory Organics	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation and reduction.

(Continued)

TABLE 14 (Continued)

Mechanism	Contaminant Affected[b]	Description
Biological		
Bacterial Metabolism[c]	P - Colloidal Solids, BOD, Nitrogen Refractory Organics	Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitrification/denitrification.
Plant Metabolism[c]	S - Refractory Organics, Bacteria and Virus.	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant Absorption	S - Nitrogen, Phosphorus, Heavy Metals, Refractory Organics	Under proper conditions, significant quantities of these contaminants will be taken up by plants.
Natural Die-off	P - Bacteria and Virus	Natural decay of organisms in an unfavorable environment.

[a] Stowell, et al. Toward the Rational Design of Aquatic Treatment Systems. University of California, Davis, 1980.

[b] P=primary effect; S=secondary effect; I=incidental effect (effect occurring incidental to removal of another contaminant).

[c] The term metabolism includes both biosynthesis and catabolic reactions.

PROCESS CAPABILITIES AND LIMITATIONS

Aquatic Plant Systems

Performance--

Water hyacinth systems are capable of removing high levels of BOD, suspended solids, heavy metals, and nitrogen, and significant amounts of trace organics. Hyacinth culture may be employed as a complete treatment process. Aquatic plant systems using duckweed show potential in achieving the same high pollutant removal efficiencies.

The addition of aquatic plants to a wastewater lagoon system can yield relative stability since the community collectively serves to buffer drastic changes. These systems are more tolerant of peak organic loadings, diurnal organic variations, and hydraulic fluctuation.

As indicated by the majority of available data, removal efficiencies of phosphorus in aquatic plant systems in excess of 30 to 50 percent cannot be consistently maintained. Phosphorus removal will not even approach that range unless there are relatively intensive management practices including regular harvesting of the plants or chemical addition precipitation is practiced. Removal of phosphorus is limited to the plant needs. Nutrient ratios in wastewater are not conducive to complete phosphorus removal, and nitrogen becomes limiting before the desired reduction in phosphates is achieved. Supplemental nitrogen addition to water hyacinth ponds may be a viable method of correcting this problem (Reference 72, 73).

Temperature and Location Constraints--

As water hyacinths are sensitive to low temperatures, temperature is the major limitation to the universal use of this tropical plant for wastewater treatment. Year-round hyacinth production in open basins is possible only in the semi-tropical and warm climates of the United States. Water hyacinth systems may be technically feasible in northern climates if operated in a protected environment, such as a greenhouse, or run on a seasonal basis. This has yet to be shown to be cost-effective for climatic zones where the plant cannot exist naturally (Reference 14).

Duckweeds are a more cold tolerant plant and offer, in theory, a greater geographical range and longer operational season than water hyacinths. However, wastewater treatment experience with these plants is limited. Many other cold tolerant aquatic plants exist, but their potential for wastewater treatment has not yet been evaluated.

By-Product Recovery--

The recovery of resources from aquatic plant systems offers a possible means of reducing the cost of wastewater treatment. Harvested plant biomass can be used in the production of fertilizer/soil conditioner, animal feed, or methane gas. All of these processes are technically feasible, but, in most cases, are not sufficiently profitable at this time to offset the costs of solids disposal (Reference 14).

Reuse Constraints--

The ability of water hyacinths and duckweeds to accumulate and concentrate toxic materials such as heavy metals and insecticides can limit their suitability as a fertilizer or feed material. The presence of toxic substances in excessive levels would make disposal of the solid materials difficult and expensive (Reference 16). There is also a need to determine if pathogens, particularly viruses, are present in the harvested and processed plants. Social, political, and economic factors could also restrict the development of plant residue products.

Evapotranspiration--

Evapotranspiration rates from uncovered hyacinth ponds have been reported up to six times greater than evaporation from open water under the same climatological conditions (References 25, 45, 107). However, these measurements may be distorted due to the small sizes of the experimental facilities as claimed by Idso (Reference 108). This controversy needs to be resolved before uncovered water hyacinth systems are used in water-short areas.

Odor Problems and Control--

Under conditions of heavy BOD loading, anaerobic conditions may prevail, as the oxygen produced by hyacinths in photosynthesis is not significant. Although water hyacinths are not affected by these conditions, odor problems may result. Mechanical aeration of the basin may be necessary during photosynthetically inactive periods to prevent foul odors (Reference 42).

Mosquito Problems and Control--

Mosquito production is encouraged in the quiet waters of an aquatic plant culture basin. Mosquito control can usually be effectively handled with Gambusia affinis or other small surface feeding species of fish stocked in the pond. Dinges recommended placing small mesh wire enclosures throughout a basin to provide open areas and enhance fish production (Reference 41).

The heavy growth of duckweeds may inhibit mosquito reproduction by preventing mosquito larvae from reaching the water surface to obtain oxygen (Reference 37).

Wind Problems and Control--

The small size of duckweeds allows the plants to be readily displaced by wind and wave action thus disrupting treatment processes. Wind screens and/ or floating barriers are usually required to maintain a continuous mat of plants on the surface of a pond (Reference 24). Placement of lagoons in protected areas or borders of vegetation that alter wind patterns can moderate such effects (Refererce 37).

Land Requirements--

Another restriction on the use of aquatic plants systems for wastewater treatment would be land area required. As these systems are land intensive, the size of the community that can use such a system may be limited.

Legal Constraints--

Introduction of water hyacinths or other exotic plants to areas where it does not currently grow may be influenced by federal and by state laws in many situations. Public Law 874, the Grass and Plants Interstate Shipment Act, Amendment to Chapter 3, Title 18, USC prohibits the interstate transport or sale of water hyacinths. The inadvertant release of these plants from a system to local waterways is a potential concern to a number of different agencies (Reference 14).

Prevention of escape of plants to the open environment by a fixed barrier in the outfall area of the basin may be one possible solution (Reference 65).

Aquatic Animal Systems

Performance--

Aquaculture systems consisting of conventional stabilization ponds followed by fish culture ponds have been shown to be capable of consistently producing secondary or advanced secondary quality effluent (Reference 15). The major role of fin fish seems to be suspended solids removal.

Certain fin fish species have demonstrated a potential for wastewater treatment application and include the carp and *Tilapia* species.

Under proper conditions, the treatment efficiency of fin fish systems should at least be comparable to AWT process treatments. However, the susceptibility of these systems to function under a wide number of variables, and their reliability to handle hydraulic/organic shock loads is unknown (Reference 109).

Wastewaters may contain a range of substances that can be toxic to aquatic animals if present at high enough levels or remain over a long enough time to create bioaccumulation problems. Industrial wastes, detergents, or biocides can effect the survival and growth of fish in wastewater ponds. System stability may also be hampered by outbreaks of diseases, parasites, and unforeseeable climatic conditions. In the event of a major animal die-off, rate of system recovery may be slow.

Dissolved Oxygen Constraints--

Dissolved oxygen is one of the most critical environmental factor which affects the functioning of an animal-based aquaculture system (Reference 92, 110). Oxygen levels become lowest prior to sunrise due to reduced oxygen production at night from reduced photosynthesis and oxygen uptake by aquatic plant and animal respiration. When this minimum is below that required for the cultured species, mortalities occur. Under minimal dissolved oxygen, fish species are also susceptible to stress from substances which they can otherwise tolerate under higher oxygen levels. Increased BOD and temperatures can also reduce the dissolved oxygen levels in wastewater ponds.

Mechanical aeration systems can be used routinely or on a standby basis in wastewater aquaculture systems to eliminate fish stress or losses during expected periods of low oxygen.

Temperature Constraints--

The use of _Tilapia_ spp. may be restricted in cold climatic areas due to their limited tolerance to low temperatures. The lower lethal temperature for these tropical fish species ranges from 10 to 13°C. The use of cold-adapted species which show potential for wastewater treatment needs to be evaluated.

In addition, only a few species of filter-feeding shellfish remain active at temperatures below 15°C, and even those become dormant at temperatures below 5°C.

By-Product Recovery--

Wide variations of fish production in wastewater ponds are indicated and are related to differences in the amount of fish initially stocked and prevailing environmental conditions in the culture unit (Reference 15). However, the benefits to fish culture, especially increases in fish yield, by using wastewaters are well documented (Reference 110). Thus, potential exists for generating large quantities of by-products from these systems.

Suggested utilization of fish products from wastewater aquaculture systems include direct human consumption, animal feed, and extraction of protein. These products have not been certified (or uncertified) by the USDA for use as yet, and the technical and economic feasibility of protein extraction has not been adequately demonstrated (Reference 15). Schemes in which direct use by human beings is avoided include fingerling fish for commercial growers, and bait fish for sportsmen (Reference 110).

Reuse Constraints--

Potential public health problems in the areas of disease transmission and contamination pose a significant barrier to the utilization of wastewater products as food stuffs in this country (Reference 10). Research on fish as a possible vector of human pathogenic bacteria, viruses, protozoans and helminths associated with enteric diseases will be required before U.S. FDA will permit these fish for human consumption (Reference 111, 112). Filter-feeding species are known for their ability to concentrate pathogenic organisms; however, these pathogens are found only in the mantle cavity and gut. Also, fish cannot act as intermediate hosts to the vast majority of human parasitic agents and the only way transmission may be effected is by direct transfer from the pond onto the fish scales or into its gut (Reference 113). Fish or animal species carrying pathogens may be depurated by keeping them in clean water for a period of time prior to marketing. Raising fish in diluted wastewater for human consumption has been the practice in Munich and other places.

While potential exists for preventing transmission of pathogens, wastewater products are also in danger of contamination by heavy metals, organic compounds, and other industrial wastes which may have carcinogenic, mutagenic, as well as teratogenic effects (Reference 111). Trace contaminants may also reach toxic concentrations when accumulated in the food chain. Permissible levels of heavy metals in treated effluent used for aquaculture have been recommended by Kerfoot and Jacobs (Reference 114) and Kerfoot and Refmann (Reference 115).

Probably the most critical drawback to products grown in a wastewater medium is that of public acceptance. Many of the social, economic, health, and political factors which influence consumer behavior in this regard have been identified (References 116 and 117), and specific marketing strategies are discussed by Huguenin and Little (Reference 118).

Land Requirements--

Another major constraint in the utilization of wastewater aquaculture treatment systems is their large land requirement. Systems involving higher forms of aquatic animals may be even more land intensive than their aquatic plant counterparts.

Legal Constraints--

Introduction of exotic fin fish species, such as the members of the carp group and *Tilapia* spp., to waters where they do not naturally occur may be influenced by federal and state laws in many situations.

The inadvertant release of these fish from a system to local waterways and their possible adverse effect on local species and envirorments are potential concerns to a number of different agencies. This limitation could be eased if research emphasis would be placed on native species of fish which also show potential in wastewater treatment. The Sacramento blackfish (*Orthodon microleclipotus*), buffalo fish (*Ictiobus* spp.) and members of the Cyprinidae family are some of the North American fishes that seem to be largely herbivorous and are also hardy.

The Food and Drug Administration, particularly through the Delaney Amendment banning any additive found to induce cancer in humans, could play a major role in determining the feasibility of by-product recovery in wastewater aquaculture. Additional health-related standards will have to be satisifed if by-products become part of the food chain (Reference 119).

Marine vs. Freshwater Systems--

Freshwater systems have a distinct advantage over marine systems for wastewater treatment application (Reference 10). Since wastewater effluents are more similar in salinity to freshwater than seawater, freshwater organisms may be cultured using undiluted effluents, whereas marine systems require extensive seawater dilutions in order to maintain a favorable salinity range for the culture organisms.

Culture Constraints--

Establishing reliable culture techniques for integrated wastewater treatment processes have been particulary difficult this far. System instability due to predation of low level organisms and lack of species control will have to be overcome before the system's treatment effectiveness can be evaluated.

Ryther et al. provided an excellent discussion concerning the factors which influence the development of aquatic populations in highly enriched marine environments (Reference 120). In general, the authors concluded that enriched marine systems are relatively unstable, failing to develop a fully diversified community and that a high degree of control and management is required to avoid inefficiencies and detrimental effects.

DESIGN CONSIDERATIONS

Design considerations for aquaculture treatment systems may be more complex than those for conventional systems as more variables are involved and many are beyond the direct control of man. In order to design an aquaculture system, an understanding of its physical characteristics, engineering criteria, and treatment capabilities as a function of system constraints, and by-product disposal/utilization are necessary (Reference 121). Aquatic organisms selected for culturing in the treatment systems must be capable of removing contaminants while surviving variable climatic and wastewater conditions. The design of the aquaculture treatment system should be formulated to provide the environment necessary for the selected aquatic species to function as intended. The recovery of resources will also effect the design of these systems.

The selection of aquatic plants and animals to be used for wastewater treatment is based, to a large extent, on their ability to provide and maintain an environment in which wastewater treatment will occur. Because the functional performance of whatever aquatic species are used will depend on their growth and behavior, the impact of factors affecting growth and behavior, such as wastewater characteristics, local environmental conditions, and operational and managerial practices must be known. Other site-specific factors in addition to wastewater treatment potential, environmental suitability, and species manageability may need to be considered when selecting organisms for use in wastewater aquaculture treatment systems.

Adequate data exist to assist in the design of water hyacinth wastewater treatment systems, especially for small capacity systems where the climate is moderate (Reference 16). Reliable engineering criteria appear to be available to justify the design of such systems for treating primary effluent, for upgrading existing systems, for advanced secondary treatment, and for full advanced wastewater treatment (Reference 14). Full-scale systems that are currently in operation and new systems being constructed should generate additional data to refine the criteria that will be presented in this section.

There is sufficient information available to install fish culture units in the final cells of stabilization ponds. However, there are not enough data available at this time to permit routine design of such units for wastewater treatment (Reference 14). Species-specific removal rates and growth rates under different environmental and wastewater conditions need further definition (Reference 15). Most of the other aquaculture systems reviewed in Section 2 have not been developed or studied sufficiently and should be considered to be in the exploratory or developmental stage. Thus, it is too early at this time to formulate even general applicable criteria for designing a reliable system. Persche, in his assessment of combined aquaculture systems, stated that firm design criteria may not be attainable practically, since some of the variables that affect system design are greatly influenced by site-specific conditions (Reference 109). The author concluded that the use of general guidelines coupled with long-term pilot studies at the proposed site may be the best approach to attaining optimum system design.

The criteria generally considered in the design of wastewater stabilization ponds, particularly physical factors, can be applied to the design of aquaculture treatment systems. These criteria are discussed in several commonly used design manuals (Reference 122). Most conventional lagoon systems can be converted with little or no modification to aquaculture systems, to upgrade effluent quality to the level of secondary or advanced secondary treatment (Reference 15). Water hyacinth wastewater treatment technology is based upon essentially the same design procedures as those for stabilization ponds.

The following design parameters should be considered and evaluated in the development of an aquaculture wastewater treatment system:

- Location, climate, temperature
- Site requirements
- Land requirements
- Wastewater characteristics
- Pretreatment
- Post-treatment
- Pond or raceway: basin size, number, and configuration
- Organic and surface loading rates
- Hydraulic residence time (detention time)
- Hydraulic loading rates
- Recovery, use or disposal of harvested biomass
- Others

These parameters are further defined for application in water hyacinth treatment systems. Procedures presented in a design manual for water hyacinth wastewater treatment by Gee and Jenson Engineers are also summarized for each of these parameters (Reference 43).

Location, Climate, Temperature

Water hyacinths should not be considered for areas where freezing conditions prevail during the winter, unless provisions are made to protect the plants from freezing or alternative treatment methods are available during the winter. Without such provisions, hyacinths should only be considered for year-round use in southern and coastal areas where temperatures are adequate for growth.

All of the water hyacinth systems in the United States that are currently treating wastewater are located in semitropical or warm temperature climates. The benefits of a system in a colder climate need to be investigated on a large scale to establish the economics as well as the operational problems, as recommended by Middlebrooks (Reference 16).

System enclosures should allow for harvesting and cleaning. The option of removal during warmer months should be evaluated. Covers should be sturdy and durable, preferably constructed of rigid plastics or frame mounted plastic sheets.

Site Requirements

The selection of a location for culture basin construction should be based on an evaluation of several site specific variables. The availability of sufficient land area for the hyacinth basins and any related treatment and disposal systems is the prime consideration. Other factors to be considered are the accessibility of the site, hydrogeological characteristics, and the method and location of final effluent disposal.

Land Requirements

All of the water hyacinth wastewater treatment systems presently operating are less than 4 hectares (10 acres) in surface area and the majority of the systems are less than 1 ha (2.5 acres) in surface area (Reference 16).

Many researchers have suggested that ponds ranging from 1 to 2 ha per 1000 cu m/day (10 to 20 acres per mgd) will provide sufficient area for secondary treatment of primary effluent and advanced treatment of secondary effluents. Reed et al. reported that based on current experience, a pond surface area of approximately 1.6 ha per 1000 cu m/day (15 acre per mgd) seemed to be reasonable for treating primary effluent to secondary or better quality (Reference 14). For systems designed to polish secondary effluent to achieve higher levels of BOD and suspended solids removal, an area of about 0.5 ha per 1000 cu m/day (5 acres per mdg) should be suitable. For enhanced nutrient removal from secondary effluent an area of approximately 1.3 ha per 1000 cu m/day (12 acres per mgd) seemed to be reasonable. A summary of these land requirements is found on Table 15.

TABLE 15. LAND REQUIREMENTS FOR WATER HYACINTH WASTEWATER TREATMENT SYSTEMS.

Treatment	Land Requirements ha per 1000 cu m/day	Land Requirements acres/mgd
Secondary treatment and advanced treatment of secondary effluents	1 to 2	10 to 20
Primary effluent to secondary or better quality	1.6	15
Polish secondary effluent	0.5	5
Nutrient removal from secondary effluent	1.3	12

Wastewater Characteristics

The characteristics of the influent wastewater and required effluent quality must be established to properly size the hyacinth pond system. Influent water quality parameters of concern include BOD_5, total suspended solids, nitrogen and phosphorus, temperature, pH, dissolved oxygen, chlorides, and toxic compounds, particularly if a portion of the influent wastewater is from industrial sources. The values obtained for these parameters should be compared against the range of tolerances for water hyacinths or other potenial aquatic plant species. The required effluent water quality will vary depending on the local conditions and applicable discharge regulations.

Pretreatment

Pretreatment of the influent wastewater prior to treatment by hyacinths or other aquatic plants may be desirable or necessary. Pretreatment may consist of one or more processes, including aeration, screening, grinding, primary settling, and chemical treatment. However, it is not always necessary to provide pretreatment in an aquatic plant system.

Post-Treatment

Post-treatment of the effluent from an aquatic plant culture basin may be necessary to meet the final effluent requirements prior to discharge. Post-treatment may include disinfection, filtration, sedimentation or other processes. Aeration may be necessary to prevent odor problems resulting from anaerobic conditions in hyacinth ponds. The addition of chemicals may be required to remove phosphorus remaining in the effluent.

Pond Size, Number, and Configuration

The considerations for pond size, number, and configuration are based on selected harvesting practices and routine maintenance. Optimal design of culture basins is necessary to minimize area requirements, and in temperate climates, greenhouse costs. The physical characteristics of optimal hyacinth culture basins were previously described in Section 1.

Organic and Surface Loading Rates

The organic loading rates used for water hyacinth treatment systems are similar to those used for conventional stabilization ponds. However, the effluent from the plant system may be better in quality than from a stabilization pond. The basic criteria used to design water hyacinth ponds for secondary treatment of primary effluent, based on Wolverton's research, are the organic uptake rate and the pond surface loading. A design value of $5.0\text{x}10^{-4}$ Kg BOD_5 per Kg wet plant mass per day ($5.0\text{x}10^{-4}$ lbs BOD_5 per pound wet plant mass per day) was recommended (Reference 42).

With water hyacinths, BOD_5 loadings up to 150 Kg per ha per day (134 lbs per acre per day) can be used, assuming an average standing crop of 225 metric tons per ha (111 tons per acre). With densely packed hyacinths and 100 percent coverage, surface loading rates of up to 225 Kg BOD_5 per ha per day (200 lbs BOD_5 per acre per day) may be used (Reference 43). The recommended surface loading rate for ponds where at least 80 percent plant coverage can be maintained ranges from 56 to 225 Kg BOD_5 per ha per day (50 to 200 lb BOD_5 per acre per day), with a recommended design value of 140 Kg BOD_5 per ha per day (125 lbs BOD_5 per acre per day) (Reference 43).

In reviewing the current full-scale water hyacinth treatment facilities, Middlebrooks reported that organic loading rates of less than 30 Kg/ha/day would provide satisfactory results when processing raw wastewater (Reference 16). Water hyacinth systems receiving secondary effluents or stabilization pond effluents are more numerous, and a much wider range of organic loading rates have been employed with these systems. Organic loading rates applied to the first basin in hyacinth systems have ranged from 31 Kg/ha/day to 197 Kg/ha/day. All of these systems produced an effluent which would satisfy the secondary standards of 30 mg/l for BOD_5 and suspended solids (Reference 42). Table 16 summarizes the various organic loading rates.

TABLE 16. ORGANIC LOADING RATES FOR WATER HYACINTH TREATMENT SYSTEMS. (Reference 42, 16, 43)

Condition	Rate
Average standing crop of 225 metric tons per ha	150 Kg BOD_5/ha/day
100% coverage	225 Kg BOD_5/ha/day
80% coverage	56 to 225 Kg BOD_5/ha/day; design value: 140 Kg BOD_5/ha/day
Processing raw wastewater	Less than 30 Kg BOD_5/ha/day
First basin in hyacinth system	31 to 197 Kg BOD_5/ha/day

Comparison of several water hyacinth systems indicated that there is a direct correlation between surface loading rates and nutrient removal efficiencies. Design curves based upon these data have been drawn up by Gee and Jenson Engineers to address nutrient removals in hyacinth tertiary treatment systems (Reference 43). Effluent requirements for nitrogen and phosphorus concentrations are used to determine the required removal efficiencies for these nutrients and thus the corresponding surface loading rates.

Hydraulic Residence Time (Detention Time)

A critical factor in aquatic plant pond design, with regard to treatment efficiencies for either secondary or tertiary systems is the contact time with the root zone of the hyacinth. It is important to allow enough time for adequate sorption, filtration, and nutrient utilization. Typical detention times for a secondary hyacinth treatment system treating primary effluent range from six to seven days, plus an allowance for sludge storage and peak flows. In a tertiary system, minimum detention times range from one day for a surface loading of 0.2 ha per 1000 cu m/day (two acres per mgd) to 5.5 days for a surface loading of 1.2 ha per 1000 cu m/day (11 acres per mgd).

Most of the studies which reported detention time for water hyacinth systems are based upon theoretical calculations (Reference 16). The degree to which the actual hydraulic residence time approaches the theoretical depends upon the care with which the original design was carried out. Tracer studies of the existing systems to determine actual detention times have been recommended.

Hydraulic Loading Rates

Based upon the results currently available, it appears that a hydraulic loading rate of 2000 cu m/ha/day when treating secondary effluent will produce an effluent quality that would satisfy advanced secondary standards ($BOD_5 \leq 10$ mg/l, $TSS \leq 10$ mg/l, $TKN \leq 5$ mg/l, and $TP \leq 5$mg/l)(Reference 16). With nutrient removal as the principal objective, a shallow pond (≤ 0.4m) and a hydraulic loading rate of approximately 500 cu m/ha/day should produce good nitrogen removals (≤ 2 mg/l). Approximately 50 percent reduction in the total phosphorus could be expected. A reasonable loading rate for a hyacinth system receiving raw wastewater was reported to be approximately 200 cu m/ha/day, if nutrient control was not an objective.

More extensive investigations will need to be conducted to determine the range of organic and hydraulic loading rates that a hyacinth system is capable of treating, particularly with systems processing raw wastewater.

Recovery of Biomass

Because there will be biomass production, the recovery of resources from aquatic plant systems offers a possible means of offsetting the cost of wastewater treatment. With intensive harvesting, it is necessary to construct the hyacinth ponds so that harvesting can be easily accomplished. Resource recovery, however, should be considered carefully if its inclusion will interfere with the performance or reliability of the aquatic plant system.

Methods of harvesting hyacinths were described in Section 2; additional information on the harvesting program will be presented in the following section under system operation and maintenance.

Other Parameters

Additional factors may need to be addressed when designing an aquatic plant system. These include sludge accumulation and storage, evapotranspiration, odor production and control, vector insect control, and other site-specific factors.

Middlebrooks in 1980 summarized design characteristics of the known aquatic plant systems that were constructed or modified to treat wastewater (Reference 16). Values were recommended to assist in the design of a system capable of producing an advanced secondary effluent. Table 17 presents the recommended design criteria.

Similar design criteria were recommended by Dinges for the construction of hyacinth basins for upgrading stabilization pond effluent in the State of Texas (Reference 41). Wolverton proposed two designs for sewage lagoons using water hyacinths and duckweeds to treat domestic wastewater. One was for small communities of 500 people or less and the other for communities of 1000 to 3000 people (Reference 42). The proposed design characteristics addressed four problems: sludge accumulation, odor control, BOD reduction, and total suspended solids removal.

Few mathematical models have been produced by the research on wastewater treatment with water hyacinths. Cornwell et al. proposed two design equations for nutrient removal by correlating nitrogen and phosphorus removal to pond surface area and flow (Reference 34). Stewart found that water hyacinths grow exponentially with time and he used the Michaelis-Menten kinetic equation to correlate the growth rate with limiting nutrient concentration (Reference 73). However, the attempts to correlate hyacinth growth rate kinetics with nutrient uptake rate as a basis for design have failed to produce a practical general design equation due to the many environmental variables that must be considered for each site (Reference 43).

ENERGY ANALYSIS

An aquaculture treatment system employs a minimal amount of equipment, and therefore, has relatively low operational

TABLE 17. DESIGN CRITERIA FOR WATER HYACINTH WASTEWATER TREATMENT SYSTEMS OPERATED IN WARM CLIMATES BASED UPON BEST AVAILABLE DATA (Reference 16)

Parameter	Design Value		Expected Effluent Quality
	Metric	English	
A. Treating Raw Wastewater To Meet Secondary Requirements			
Hydraulic Residence Time	$>$ 50 days	$>$ 50 days	SS $\leq$30 mg/l
Hydraulic Loading Rate	200 cu m/ha/day	0.0215 mgd/acre	
Depth, Maximum	$\leq$ 1.5 meters	$\leq$ 5 feet	
Area of Individual Basins	0.4 hectare	1 acre	
Organic Loading Rate	$\leq$ 30 kg BOD$_5$/ ha/day	$\leq$ 26.7 lbs BOD$_5$/ac/day	
Length to Width Ratio of Hyacinth Basin	$>$ 3:1	$>$ 3:1	
Water Temperature	$>$ 10°C	$>$ 50°F	
Mosquito Control	Essential	Essential	
Diffuser at Inlet	Essential	Essential	
Dual Systems, Each Designed to Treat Total Flow	Essential	Essential	
B. Treating Secondary Effluent to Advanced Secondary			
Hydraulic Residence Time	$>$ 6 days	$>$ 6 days	SS $\leq$10 mg/l
Hydraulic Loading Rate	800 cu m/ha/day	0.0855 mgd/acre	TP $\leq$5 mg/l
Depth, Maximum	0.91 meter	3 feet	TN $\leq$5mg/l
Area of Individual Basins	0.4 hectare	1 acre	
Organic Loading Rate	$\leq$ 50 kg BOD$_5$/ ha/day	$\leq$ 44.5 lbs BOD$_5$/ac/day	
Length to Width Ratio of Hyacinth Basin	$>$ 3:1	$>$ 3:1	
Water Temperature	$>$ 20°C	$>$ 68°F	
Mosquito Control	Essential	Essential	
Diffuser at Inlet	Essential	Essential	
Dual Systems, Each Designed to Treat Total flow	Essential	Essential	
Nitrogen Loading Rate	$\leq$ 15 kg TKN/ ha/day	$\leq$ 13.4 lbs TKN/ac/day	

requirements as compared to a conventional treatment plant. Energy is required for pumping (in some cases), harvesting equipment and trucks for hauling harvested solids.

Pumping may be required for static lift between the pretreatment effluent discharge and the aquaculture system inlet, and/or to provide gravity flow through the aquaculture basin. A reasonable range would be between 0 and 3 meters (0 to 10 feet) of head. The energy required will be a function of the amount of hours the pumps will be in operation.

Table 18 summarizes the power and energy demands at various flows and for the conservative conditions of a 3 meter static lift and continual operation (24 hours a day, 365 days a year). The table shows that the annual pumping energy demands are quite small.

TABLE 18. PUMPING ENERGY DEMANDS FOR AN AQUACULTURE SYSTEM, ASSUMING A 3 METER STATIC LIFT

Flow cu m/day	kW[a]	MJ/year[b]	kWh/year[b]
400	0.170	5,364	1,490
800	0.34	10,728	2,980
2000	0.85	26,820	7,450
4000	1.7	53,640	14,900
8000	3.43	107,280	29,800

[a] Assuming a wire to water pumping efficiency of 80 percent
[b] For continuous use; 365 days a year and 24 hours a day

There are many potential methods of harvesting the water hyacinths. The estimate herein is based on a conventional aquatic weed harvesting system. This may not be a reasonable assumption for the smaller systems where fairly simple harvesting techniques may be used, but for this cost and energy analysis some assumptions and simplifications must be made. This system includes a harvester and a shore conveyor which is fully automatic and requires only one operator to drive the harvester. The shore conveyor conveys the harvest back up onto the land where it is dropped into a dump truck. The following assumptions were used in the estimate:

- Harvesting volume = 440 wet metric tons/ha/year
- Harvesting capacity = 2.27 metric tons/load
- Total operating time, including harvesting, unloading and transport = 0.66 hours/wet metric ton or 290 hour/ha/year

- The harvester and conveyor are driven by small gasoline engines.

- Energy requires 1.58×10^5 kJ/hour (44.0 kWh/hour)

Therefore, the energy required is 9.18×10^7 kJ/ha/year (1.03×10^4 kWh/acre/year).

The harvested solids are assumed to be disposed of on-site, either by land application or in a landfill. The estimates for energy consumed in solids disposal are based on the following:

- A 1.6 kilometer (1 mile) round trip between hyacinth pond and disposal area.

- Dump truck fuel efficiency of 2.13 kilometers/liter gasoline (5 miles/gal).

- Each load is 2.7 m.t. (3 tons).

Therefore, the energy for solids disposal is 3.44×10^6 kJ/ha/year (386 kWh/acre/yr). The total energy required for harvesting and disposal is 9.52×10^7 kJ/ha/year (1.07×10^4 kWh/acre/year, 364 gal/acre/year).

For this energy analysis it is assumed that the harvested solids have no potential value. This is based on the fact that none of the full scale facilities are deriving any financial or energy value from the harvested solids. The Reedy Creek Facility is studying the anaerobic digestion of water hyacinth at a bench scale level.

OPERATION AND MAINTENANCE REQUIREMENTS

Aquaculture treatment systems function under a number of variables, many of which are beyond the control of the operator. Therefore, operation and maintenance requirements are minimal for these systems, with only a few control variables required for the adjustment of treatment efficiency. The process variables that can be controlled allow the system, if properly designed, to be operated at a constant design efficiency.

O&M practices for aquaculture treatment systems will vary depending on the species selected. The match between the environment, as determined by wastewater characteristics and climate, and the environmental requirements of the selected species needed to optimize their function in the treatment process will rarely be perfect. Tchobanoglous et al. reported that managerial practices are an additional aspect of the aquaculture concept that, if applied, can create an environment closer to the optimum for the selected species. These may include pretreatment of the wastewater, aeration, controlled recirculation, control of residence times, and biomass harvesting (Reference 121).

Control of water hyacinth treatment systems is accomplished by plant harvesting, basin cleaning, and, to a lesser extent, control of environmental conditions and influent characteristics (Reference 43). Hyacinth and sludge processing and disposal should also be considered during design as an important O&M factor. Odor, insect, and other nuisance conditions may develop and have to be controlled.

The frequency of plant harvesting is dependent upon the required effluent quality, plant condition and climatic factors. Generally, more frequent harvests will be required during the hotter months of the year. In colder regions where only seasonal operation will be permitted (unless adequately protected), all hyacinths should be removed from the culture basins during the freezing period to prevent the hyacinths from dying and settling to the pond bottom. During periods of accelerated plant growth, it has been recommended that harvesting be performed at least once every two weeks. Hyacinths that exhibit a slower growth rate, leaf yellowing, or other unhealthy characteristics should be removed from the culture basins during harvest. Systems designed for secondary treatment can be harvested less frequently. However, they may need to be harvested at least once per month during hotter, rapid growth periods of the summer season.

The optimum harvesting program should be predicated on a hyacinth removal rate that maintains a constant coverage in the ponds. Where constant coverage is not practical, the harvesting program should be based upon observations and measurements of the system effluent quality and plant condition. In order to prevent algae blooms and to maintain an adequate treatment efficiency at all times, it has been recommended that no more than 20 percent of the pond surface area be harvested at any one time.

A wastewater management system is complete only with proper disposal or utilization of residual by-products. Harvested water hyacinths may need to be processed following harvesting to reduce the moisture content and bulk of the plants to simplify disposal/reuse. There are several alternative disposal methods suitable for properly processed hyacinths. Processing methods and disposal/reuse alternatives have been previously discussed in Section 2.

Basin cleaning may be necessary to prevent excessive build-up of solids and plant debris on the basin bottom. Sludge accumulation in hyacinth ponds does not appear to be a significant problem since the solids undergo decomposition. However, ponds that may accumulate excessive solids need to be taken out of service, emptied and cleaned as necessary to prevent reductions in removal efficiency. Tertiary treatment ponds should be cleaned as required to maintain adequate treatment efficiency. Secondary treatment systems should be cleaned at least once every five to ten years, or as required by the accumulation of sludge and solids deposits on the basin bottom.

COST ANALYSIS

Cost estimating procedures used in this report follow the U.S. EPA's cost-effectiveness guidelines (Reference 123). Cost effectiveness is defined to include monetary cost and environmental and social impact assessment. Capital cost estimates are based on the Engineering News Record Construction Cost Index (ENR CCI) 20 cities average, March 1981. Capital costs are based on an operable system with a 20-year life. If a system has an expected service life of less than 20 years, the O&M cost includes the annual present worth of subsequent replacement required to obtain a 20-year service life. Salvage value for estimated service life beyond 20 years is considered for land as allowed by the EPA guidelines.

Capital costs include construction, engineering, legal, administration and contingencies for all building, equipment and appurtenances. Annual operation and maintenance costs include labor, energy, chemicals and routine replacement of parts and equipment. Equipment cost estimates were based on preliminary layouts and sizing, appropriate redundance, quotations from equipment manufacturers and recent contract bids as available. Operating cost escalations are projected to be approximately 10 percent per year. The assumptions made for the energy estimates in the previous energy section apply.

Basic cost assumptions include:

Service life = 20 years

Life cycle cost interest rate (EPA required) = 7 percent

Non-component costs = Piping @ 10%

Non-component costs = Piping @ 10%
Electrical @ 8%
Instrumentation @ 5%
Site preparation @ 5%
Total = 28% of construction costs

Non-construction costs = Engineering and construction supervision @ 15%
Contingencies @ 15%
Total = 30% of construction and non-component costs

Capital cost = Construction cost plus non-component and non-construction costs

Capital recovery factor = 20 years, 0.09439, 7%

Present worth factor = 10.594 times annual operating cost

ENR CCI (20 cities average March, 1981) = 3384

Labor cost, rural community (March, 1981) = $11/hour

Energy cost (March, 1981)
Electricity (industrial rate) = $.011/MJ ($0.04/kilowatt hour)
Gasoline = $0.396/liter ($1.50/gallon)

Energy cost escalation factor
Electricity
1980-1990 = 28%
1990-2000 = 6%
Gasoline
1980-1990 = 34%
1990-2000 = 21%

In order to estimate the costs which are associated with an aquaculture system, assumptions were made to narrow the wide range of possibilities. The capital and O&M costs of an aquaculture system are based primarily on the type of system (aquatic macrophytes, invertebrates, integrated, etc.) and the necessary surface area. Of the four categories of aquaculture, aquatic plants are the most developed, and specific design criteria have been published for these systems. Within the aquatic plants category, the most work has been done on water hyacinths. Since the most reliable data have been developed for water hyacinth systems, they will be used for the cost evaluation.

Hyacinth systems are sized on surface and organic loading rates. These rates vary for different influent and effluent quality. Three probable applications have been developed for the cost evaluation to illustrate how costs relate to the varing degrees of treatment.

Case 1:

Treatment Quality

	Concentrations (mg/l)			
	BOD_5	TSS	N	P
Influent - Primary effluent	150	100	40	8
Effluent - Secondary	30	30	40	8

Design Criteria from Table 17:
Organic loading = 100 kg BOD_5/ha/day, 89 lb BOD_5/acre/day
Depth = 1.5m, 5 ft

Therefore:
Surface loading = 1.5 ha/1,000 cu m/day, 14 acre/mgd
Volume = 2.25×10^4 cu m/1,000 cu m/day

Case 2:

Treatment Quality

	Concentrations (mg/l)			
	BOD_5	TSS	N	P
Influent - Secondary effluent	30	30	40	8
Effluent - Advanced secondary	10	10	10	5

Design Criteria from Table 17:
Organic loading = 50 kg BOD_5/ha/day, 47 lb BOD_5/acre/day
Depth = 0.91 m, 3 ft

Therefore:
Surface loading = 0.6 ha/1,000 cu m/day, 5.6 acres/mgd
Volume = 5460 cu m/1,000 cu m/day

Case 3:

Treatment Quality

	BOD₅	TSS	N	P
	Concentrations (mg/l)			
Influent - Advanced Secondary	10	10	10	5
Effluent - AWT	5	5	3.5	3.5

Design criteria based on the results frcm full scale application at Lakeland, FL and Coral Spring, FL.

Surface loading = 2.64 ha/1,000 cu m/day, 24.6 acre/mgd
Depth = 0.5m, 1.6 ft

Therefore:
Organic loading = 3.78 kg BOD_5/ha/day, 3.37 lb BOD_5/acre/day
Volume = 1.32×10^4 cu m/1,000 cu m/day

Based on the above values the total surface area was computed and is tabulated in Table 19.

TABLE 19. SURFACE AREA REQUIRED FOR WATER HYACINTH AQUACULTURE SYSTEMS, HECTARES

Flow (cu m/day)	Case 1 (Secondary)	Case 2 (Advanced Secondary)	Case 3 (AWT)
400	0.6	0.24	1.1
800	1.2	0.48	2.1
2000	3	1.2	5.0
4000	6	2.4	11.
8000	12	4.8	21.

Capital costs include earthwork, land acquisition, pumps, harvesting equipment, greenhouse structure, and artificial liners.

To obtain advanced waste treatment (AWT) from an influent of primary effluent the three cases can be added in series. Other combinations are also possible.

The major construction cost is for earthwork which includes excavation, grading, berm construction, and compaction. The current cost is approximately $6.50/cu m ($5/cu yd). Table 20 lists the approximate cost of earthwork, for various flows, for all three cases. The total present worth cost of a new aquaculture system is most sensitive to the earthwork cost. If existing basins or ponds are used, earthwork cost becomes less significant.

TABLE 20. COST ESTIMATES OF EARTHWORK FOR WATER HYACINTH AQUACULTURE SYSTEMS, $ THOUSAND, ENR CCI 3384*

Flow (cu m/day)	Case 1	Case 2	Case 3
400	$ 58.5	$ 14.3	$ 34
800	117	28.3	69
2000	293	73.3	172
4000	585	142.7	343
8000	1,170	285	690

* Based on $6.50/m^3 of excavation

The cost of land acquisition varies across the country. While some agencies already own available land, others must purchase a suitable site. In addition, many aquaculture systems involve conversion of existing pond systems. The estimated range for land purchase used in this analysis is $2,470-4,942 per hectare ($1,000-2,000 per acre). Since aquaculture systems are land intensive it is important to consider the cost of land where applicable for a specific system cost analysis. Table 21 summarizes the range in land acquisition costs for the three cases at various flows. The salvage value of the land is considered in the present worth cost analysis.

The sensitivity of the total present worth cost of an aquaculture system to land acquisistion cost was evaluated using the design examples presented in Tables 27, 28, and 29. The land acquisition cost of $3,000/ha ($1,335/acre) was used for these tables resulting in about 1 to 2 percent of the total present worth cost. If land acquisition cost were increased ten-fold to $30,000/ha ($13,350/acre), the percent of total present worth cost would be 9 to 10 percent.

A portion of the land acquisition cost (about 50 percent) is recovered in the analysis as a salvage cost. As allowed by grant regulations, land values can be appreciated at a compound interest rate of 3 percent/year over the planning period (20 years in this case) or a factor of 1.806. The present worth of the salvage value at the end of 20 years is calculated by multiplying that value by the single payment present worth factor at 7 percent for 20 years or 0.2584. The salvage value (land value at the end of 20 years) therefore reduces the impact of land acquisition cost or the total present worth cost of the aquaculture system. If existing facilities are used (e.g. oxidation ponds), then land acquisition costs are not significant.

TABLE 21. COST OF LAND ACQUISITION FOR WATER HYACINTH AQUACULTURE SYSTEM, $ THOUSAND, ENR CCI 3384*

Flow (cu m/day)	Case 1	Case 2	Case 3
400	$ 1.5-3.0	$ 0.5-1.2	$2.5-6.0
800	3.0-6.0	1.3-2.4	5-10
2000	7.4-14.8	3-6	12.6-24
4000	15-30	6-12	27-64.3
8000	30-60	12-24	54-98.8

* Based on $2,500 to $5,000 hectare

If pumping is required, capital expenses will be encountered for pumps, a pump station and piping. Approximate capital costs associated with pumping are shown on Table 22.

The cost of the harvesting equipment is based on the system described in the preceding section. The total capital cost is about $91,000, which can be broken down to $69,500 for the harvester, $16,000 for the shore conveyor and $5,500 for the trailer.

TABLE 22. CAPITAL COST OF PUMPS, PUMP STATION AND PIPING, ENR CCI 3384 (Reference 125)

Flow cu m/day	Cost $1000
400	21.5
800	33
2000	44
4000	82
8000	123

A dump truck will be used for hauling the dewatered solids to the disposal area. It is assumed that the municipality will already own a dump truck that could be used for this purpose. Therefore, it will not be necessary to include the capital cost of the truck. An appropriate portion of the truck's maintenance and replacement costs will be included in the operation budget.

For most applications the hyacinth basins can be sealed with a clay liner. Under some circumstances an artifical liner will be required to prevent seepage of the wastewater into the the groundwater. Artifical liners are expensive, ranging from $12 to $37 per sq m. Table 23 presents a range of costs for artificial liners for each case at various flows.

TABLE 23. COST OF ARTIFICIAL LINER FOR A WATER HYACINTH AQUACULTURE SYSTEM, $ MILLION, ENR CCI 3384*

Flow (cu m/day)	Case 1	Case 2	Case 3
400	0.072-0.22	0.024-0.075	0.13-0.41
800	0.144-0.44	0.048-0.15	0.25-0.82
2000	0.36-1.1	0.12-0.38	0.65-2.1
4000	0.72-2.2	0.24-0.75	1.3-4.1
8000	1.44-4.4	0.48-1.5	2.5-8.2

* Based on $12 to $37/m^2 of liner

As discussed in previous sections, aquaculture systems located in colder climates may require greenhouses to insure proper temperature for plant growth. The actual cost of a greenhouse varies depending on the design, method and materials of construction and environmental conditions. Costs of existing greenhouses and quotes on greenhouses for systems in the design stage range from $27 to $108 per sq m ($2.5 to $10 a sq ft).

O&M cost estimates were developed for labor, replacement of equipment, maintenance of equipment and fuel consumed.

The labor costs can be broken down between daily operation and harvesting. The annual hours for labor have been estimated by Robinson (Reference 27) for various surface areas using a logarithmic relationship and include operation and maintenance labor, and administration. Table 24 shows labor hours for the three cases.

TABLE 24. ANNUAL LABOR HOURS - EXCLUSIVE OF HARVESTING AND SOLIDS DISPOSAL (REFERENCE 27)

Flow (cu m/day)	Case 1	Case 2	Case 3
400	160	90	230
800	230	130	300
2000	360	225	480
4000	540	325	740
8000	750	470	1050

The estimate of the labor demands for harvesting are for the same harvesting system as described in the energy and capital cost section. The equipment requires only one operator. The unit labor demand is 290 hours per hectare per year which includes the actual harvesting time, unloading and transport time. The labor required by the truck driver for the solids disposal is 10 hours per hectare per year. Therefore, the total labor required for harvesting is 300 hours per hectare per year. Table 25 presents the total labor required for the harvesting and solids disposal.

TABLE 25. TOTAL ANNUAL LABOR HOURS REQUIRED FOR THE HARVESTING AND DISPOSAL OF AQUACULTURE SYSTEM SOLIDS

Flow (cu m/day)	Case 1	Case 2	Case 3
400	180	72	330
800	360	144	630
2000	900	360	1500
4000	1800	9720	3300
8000	3600	1440	6300

The total operation and maintenance costs include maintenance of the aquaculture system harvesting equipment, solids disposal truck, pumps, and the replacement cost of the harvesting equipment which has an expected life of 10 years, and the cost of the energy expended. The unit cost of the equipment maintenance is $256 per ha per year. It is assumed that the cost of maintaining the hauling truck will be shared among the various agencies in the community. The annual maintenance cost is estimated to be 5% of the capital cost, or $1750 a year. Pumps are assumed to have a 20 year life and an annual maintenance cost of 5 percent of the capital cost. The annual maintenance of the aquaculture system (e.g., levee and piping repairs) is estimated to be 0.5 percent of the capital earthwork costs. In ten years and at a 7 percent annual increase, the replacement cost of the harvesting equipment will be about $179,000. The annual replacement cost over 20 years is $8,590. The annual energy cost estimate includes the cost for the energy demands described in the energy analysis, plus an additional 10 percent for miscellaneous energy uses.

The total operation and maintenance cost for an aquaculture system is shown in Table 26.

TABLE 26. ANNUAL OPERATION AND MAINTENANCE COST FOR AN AQUACULTURE SYSTEM, ENR CCI 3384

Flow (cu m/day)	Case 1	Case 2	Case 3
400	$ 5,110	$ 4,400	$ 4,050
800	8,200	6,790	5,790
2000	25,550	22,000	20,250
4000	33,100	26,000	20,500
8000	64,000	49,900	42,930

There are 15 situations (3 different cases and 5 different flow rates) which could be analyzed. To keep this assessment concise, only one flow rate will be used for the 3 cases studied for the detailed cost analysis. The methodology used for the cost estimate can be applied for any of the flow rates and combination of cases. A flow rate of 4000 cu m day (1.06 mgd) has been chosen as the representative flow for small communities. Other assumptions include:

- System operating 12 months/year
- Pumping required to overcome a 3 meter static lift
- Artificial liner not required
- Greenhouse not required
- Land costs at $3,000/ha ($1,335/acre)
- The salvage value of land is calculated by escalating the purchase price by 1.806 (appreciation at a compound interest rate of 3 percent/year for 20 years). The present worth of the salvage value at the end of 20 years is that value multiplied by the single pay-

ment present worth factor at 7 percent for 20 years (0.2584).

The average annual cost for Case 1, primary effluent to secondary, is $76,100, for Case 2, secondary effluent to advanced secondary, is $82,200, and for Case 3, advanced secondary effluent to AWT, is $166,800. The cost breakdowns are presented for each case in Tables 27, 28 and 29.

TABLE 27. ESTIMATED COSTS FOR AN AQUACULTURE SYSTEM, CASE 1, 4,000 cu m/day, ENR CCI 3384

Item	Capital	Annual O&M	Present Worth O&M	Total Present Worth	Average Annual
Earthwork	$ 585,000	$ 2,900			
Land Acquisition	18,000				
Pumping	82,000	4,100			
Harvesting equipment	91,000	8,590			
Labor	—	25,740			
Dump truck for solids disposal	—	1,750			
Misc. equipment	—	1,540			
Subtotal 1	776,000				
Non-component costs @ 28%	217,000				
Subtotal 2	993,000				
Non-construction costs @ 30%	298,000				
Subtotal 3	1,291,000	44,620	$ 472,700	$1,763,700	$ 166,480
Energy-electricity		600	7,124	7,124	672
Energy - gasoline		8,100	103,210	103,210	9,740
Subtotal 4				1,874,000	176,890
Land Salvage Value (subtract)				8,400	790
TOTAL				$1,865,600	$176,100

TABLE 28. ESTIMATED COSTS FOR AN AQUACULTURE SYSTEM, CASE 2, 4000 cu m/day, ENR CCI 3384

Item	Capital	Annual O&M	Present Worth O&M	Total Present Worth	Average Annual
Earthwork	$142,700	$ 715			
Land acquisition	7,200	—			
Pumping	82,000	4,100			
Harvesting equipment	91,000	8,590			
Labor	—	11,500			
Dump truck for solids disposal	—	1,750			
Mics. equipment	—	610			
Subtotal 1	323,000				
Non-component costs @ 28%	90,000				
Subtotal 2	413,000				
Non-construction costs @ 30%	124,000				
Subtotal 3	537,000	27,260	288,850	825,900	77,950
Energy-electricity		600	7,124	7,124	672
Energy-gasoline		3,240	41,300	41,300	3,900
Subtotal 4				874,300	82,500
Land Salvage Value (subtract)	0	0	0	3,340	320
TOTAL				$871,000	$ 82,200

TABLE 29. ESTIMATED COSTS FOR AN AQUACULTURE SYSTEM, CASE 3, 4000 cu m/day, ENR CCI 3384

Item	Capital	Annual O&M	Present Worth O&M	Total Present Worth	Average Annual
Earthwork	$343,000	$ 1,700			
Land acquisition	33,000	—			
Pumping	82,000	4,100			
Harvesting equipment	91,000	8,590			
Labor	—	44,440			
Dump truck for solids disposal	—	1,750			
Misc. equipment	—	2,820			
Subtotal 1	549,000				
Non-component costs @ 28%	154,000				
Subtotal 2	703,000				
Non-construction costs @ 30%	211,000				
Subtotal 3	914,000	63,400	$671,700	$1,585,700	$149,700
Energy-electricity		600	7,124	7,124	672
Energy-gasoline		14,850	189,300	189,300	17,868
Subtotal 4				1,782,100	168,240
Land Salvage Value (subtract)				15,400	1,450
TOTAL				$1,766,700	$166,800

SECTION 5

COMPARISON WITH EQUIVALENT CONVENTIONAL TECHNOLOGY

COST COMPARISON

A range of average annual costs for conventional secondary and advanced treatment systems was developed for this comparison by completing a present worth analysis based on the construction and annual O&M cost data given in the EPA I/A Manual (Reference 125). These costs are the unit costs for various secondary and advanced secondary treatment systems. The cost of treating the influent prior to the secondary, advanced secondary, or AWT process is not included since these costs are similar for the conventional and aquaculture systems. The cost of the following conventional secondary treatment systems were included in the development of the cost curves: activated sludge (mechanical aeration, high rate diffused aeration, and pure oxygen), trickling filters, stabilization ponds, rotating biological contactors, and contact stabilization. The cost of the following processes were used for conventional advanced secondary and AWT cost curves: dual media filters, activated carbon, nitrification, Phostrip, ion-exchange, tertiary lime treatment and ferric chloride addition.

The costs for conventional technology include solids separation and sludge disposal. The costs for aquaculture systems include hyacinth harvesting and disposal but do not include sludge disposal since it was assumed that sludge disposal would not be necessary.

The range of costs are presented in two graphs, Figure 5 for secondary treatment and Figure 6 for advanced secondary and AWT. These figures show the average annual cost as a function of the plant's capacity for both the conventional and aquaculture systems. The aquaculture system curves are based on the cost estimate detailed in Section 4.

The average annual cost is based on two cost components, the capital and the annual O&M costs. Curves for each of these components were developed from Reference 125. Figure 7 shows the capital cost as a function of plant capacity for secondary systems, and Figure 8 for advanced and AWT systems.

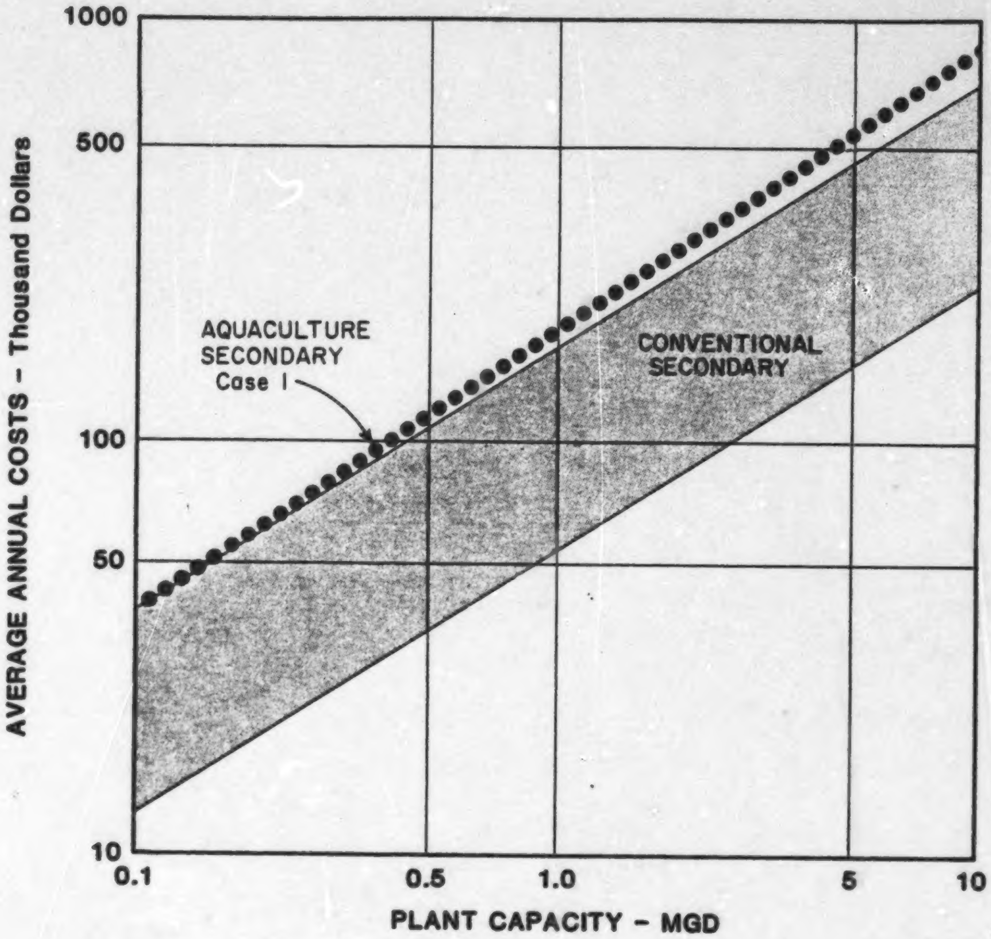


FIGURE 5. Average Annual Costs Comparison - Secondary Treatment

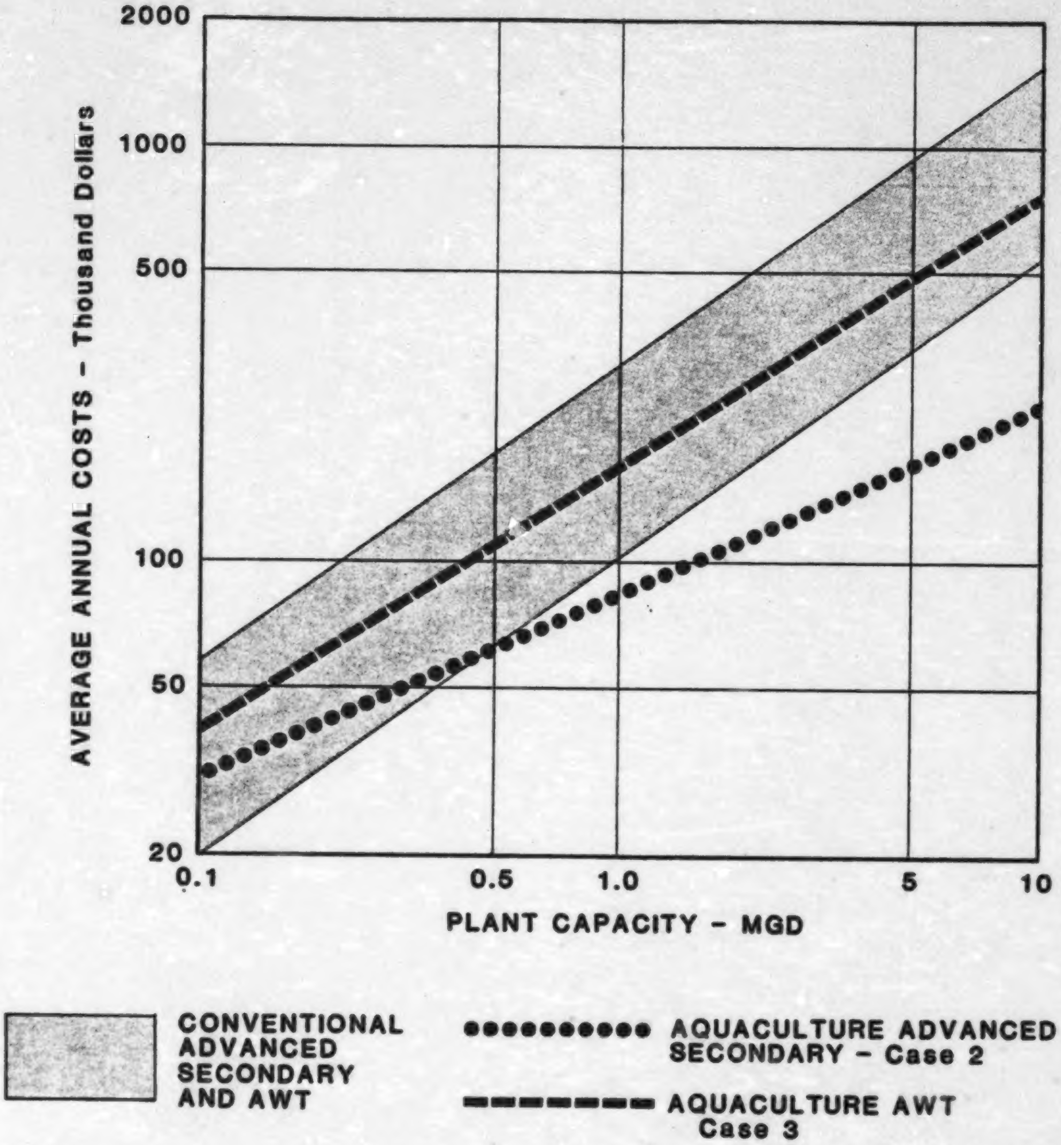


FIGURE 6. Average Annual Costs Comparison - Advanced Treatment.

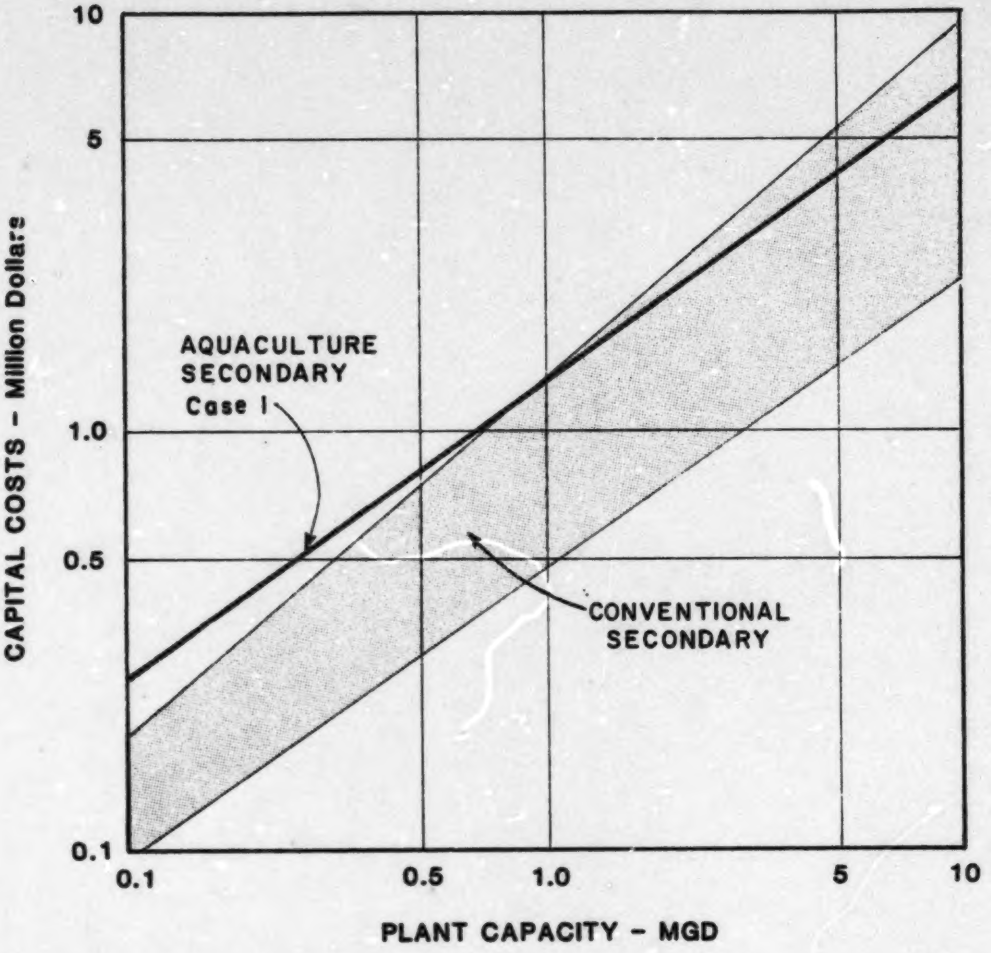


FIGURE 7. Capital Cost Comparison –Secondary Treatment.

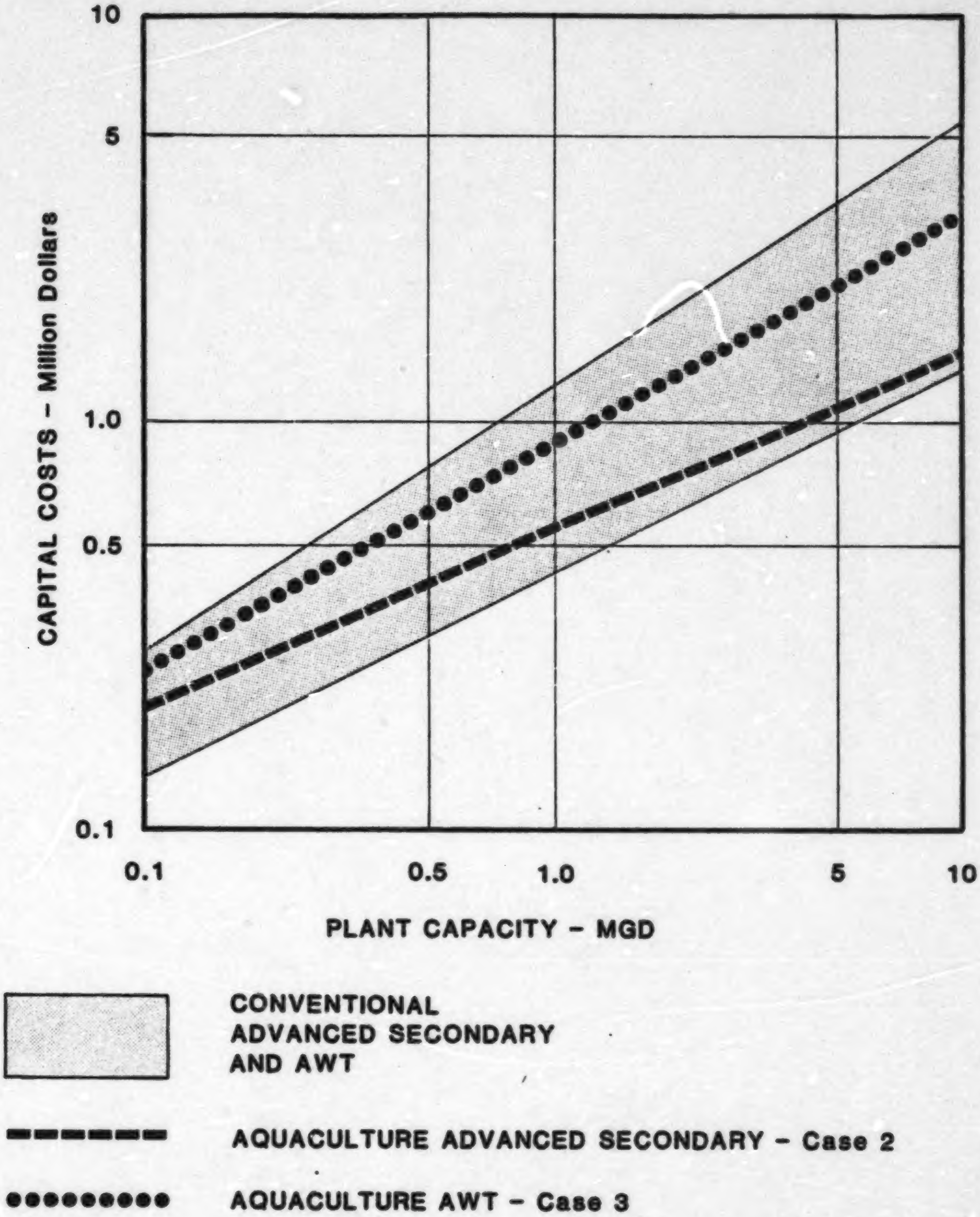


FIGURE 8. Capital Cost Comparison - Advanced Treatment.

A graph showing the annual O&M cost as a function of plant capacity is shown in Figure 9 for secondary systems and Figure 10 for advanced and AWT systems.

It is important to note that the costs presented are for the construction and operation of original aquaculture systems. Many full scale facilities such as those located in Texas involved conversion of existing pond systems. The construction costs were, therefore, relatively low because the volume of earthwork was less and much of the labor was done by city employees. The actual construction costs for many of these facilities, however, have not been determined by the respective agencies.

The advanced secondary (Case 2) system with a capacity greater than 1,890 cu m/day (0.5 mgd) is less expensive on an average annual basis than a conventional system. The average annual cost for other capacity and treatment levels is within the range of the conventional system costs.

Evaluation of Figures 7 and 8 indicate that capital costs for aquaculture advanced treatment systems, Case 2 and 3, are competitive with the conventional system capital costs. For secondary treatment (Case 1), the capital cost comparison is split; aquaculture systems with capacity greater than 3,785 cu m/day (1 mgd) are cost competitive, and capacities less than 3,785 cu m/day are more costly to construct than conventional systems.

Review of the annual O&M cost curves (Figures 9 and 10) indicates that for Case 1 and Case 3, advanced secondary and AWT, the annual O&M costs are within the range of conventional systems. For the advanced secondary aquaculture systems (Case 2), the O&M costs are less than conventional systems for plants with greater than 1,890 cu m/day (0.5 mgd) capacity, and are competitive with conventional systems for plants with less than 1,890 cu m/day capacity.

ENERGY COMPARISON

The energy requirements for conventional treatment systems were determined from References 126 and 127. The conventional secondary systems considered are activated sludge with clarification, trickling filter, rotating biological contactors, and contact stabilization. The conventional advanced and AWT systems used for comparison are activated carbon, dual media filter, nitrification, Phostrip, ion-exchange (for ammonia removal) and ferric chloride addition. The aquaculture system's demands are based on the assumptions and discussion

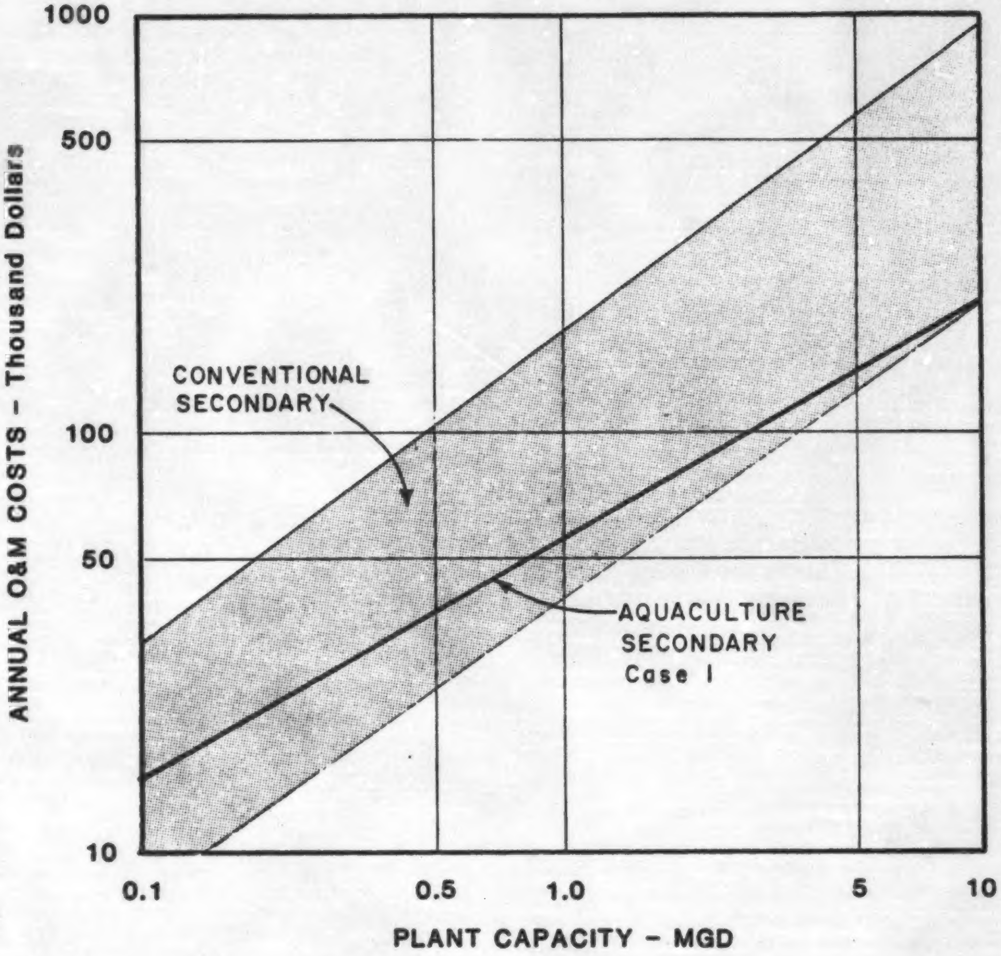


FIGURE 9. Annual O&M Cost Comparison - Secondary Treatment.

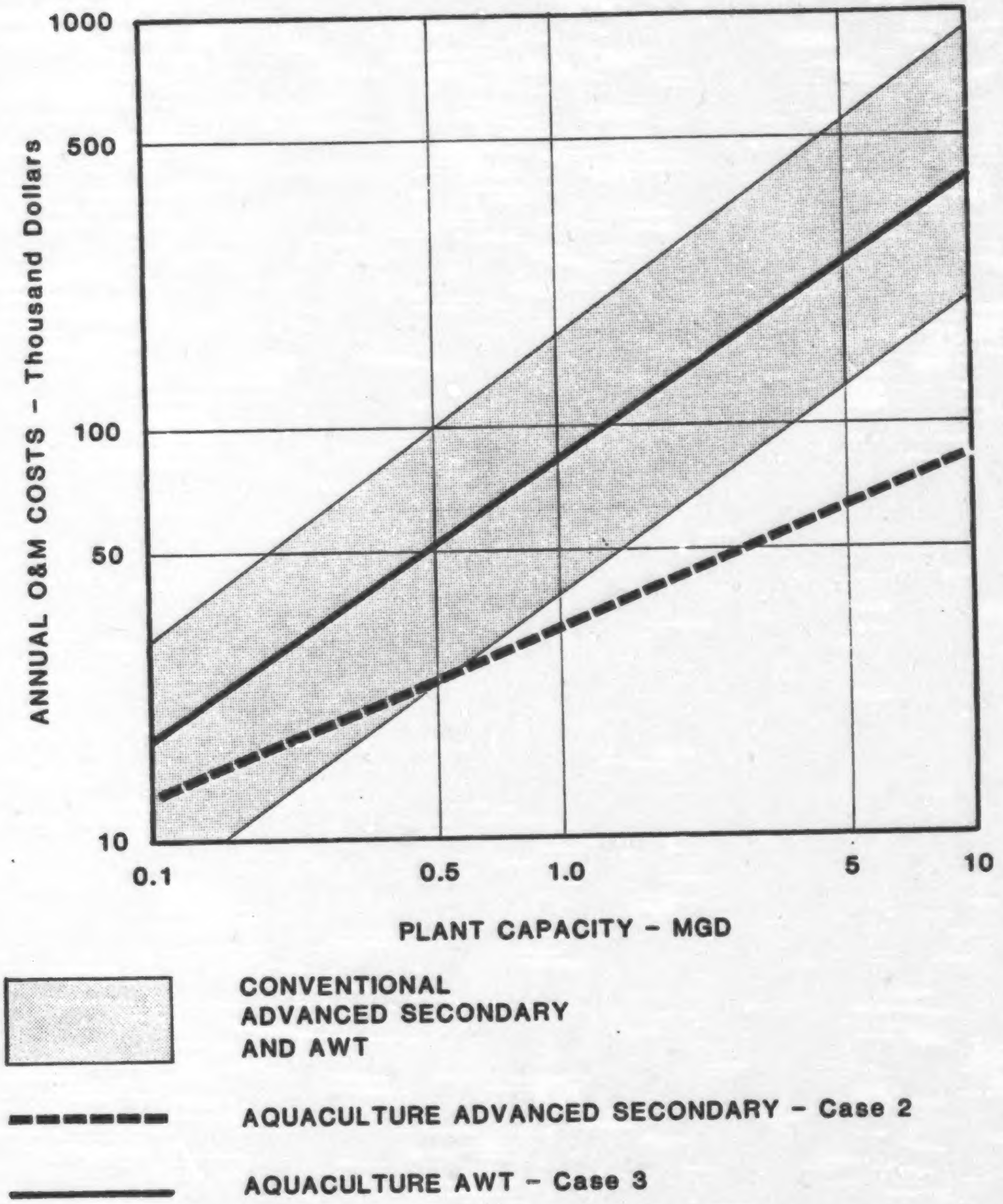


FIGURE 10. Annual O&M Cost Comparison - Advanced Treatment.

presented in Section 4. These energy demands include solids separation and disposal.

As with the cost comparison, the conventional system energy demands have been compared with the aquaculture system demands as a function of plant capacity as shown in Figure 11 and 12. Since the harvesting process consumes energy in the form of gasoline, the comparison between the aquaculture and conventional plants is made in Btu's. In converting the electrical kWh demand into equivalent Btu's, a conversion efficiency of 33 percent was used.

Figure 11 shows that secondary treatment using an aquaculture system (Case 1) consumes less energy than a conventional system. Estimated savings for secondary systems are shown in Table 30. Since the energy demand for the conventional system is presented as a range in Figure 11, the midpoint energy value for the selected flow rates is used for the comparison. As Table 30 shows annual savings of 74 to 85 percent.

Conventional and aquaculture advanced secondary and AWT are compared in Figure 12. Both advanced secondary and AWT are within the range developed for conventional advanced secondary and AWT.

The energy demands of the aquaculture systems are primarily due to the harvesting requirements (440 wet metric tons/ha/year) and hyacinth disposal. If the harvesting requirements of a specific system can be reduced, the energy costs would be reduced and may compare more favorably with that of the conventional systems.

TABLE 30. COMPARISON OF AQUACULTURE AND CONVENTIONAL SECONDARY SYSTEM ANNUAL ENERGY REQUIREMENTS (Btu/yr)

	Flow Rates cu. m./day			
Treatment Type	400	2000	4000	8000
Conventional	3.91×10^8	1.56×10^9	3.19×10^9	1.07×10^{10}
Aquaculture	8.14×10^7	4.07×10^8	8.14×10^8	1.63×10^9
Savings	3.10×10^8	1.15×10^9	2.38×10^9	9.07×10^9
	79%	74%	74%	85%

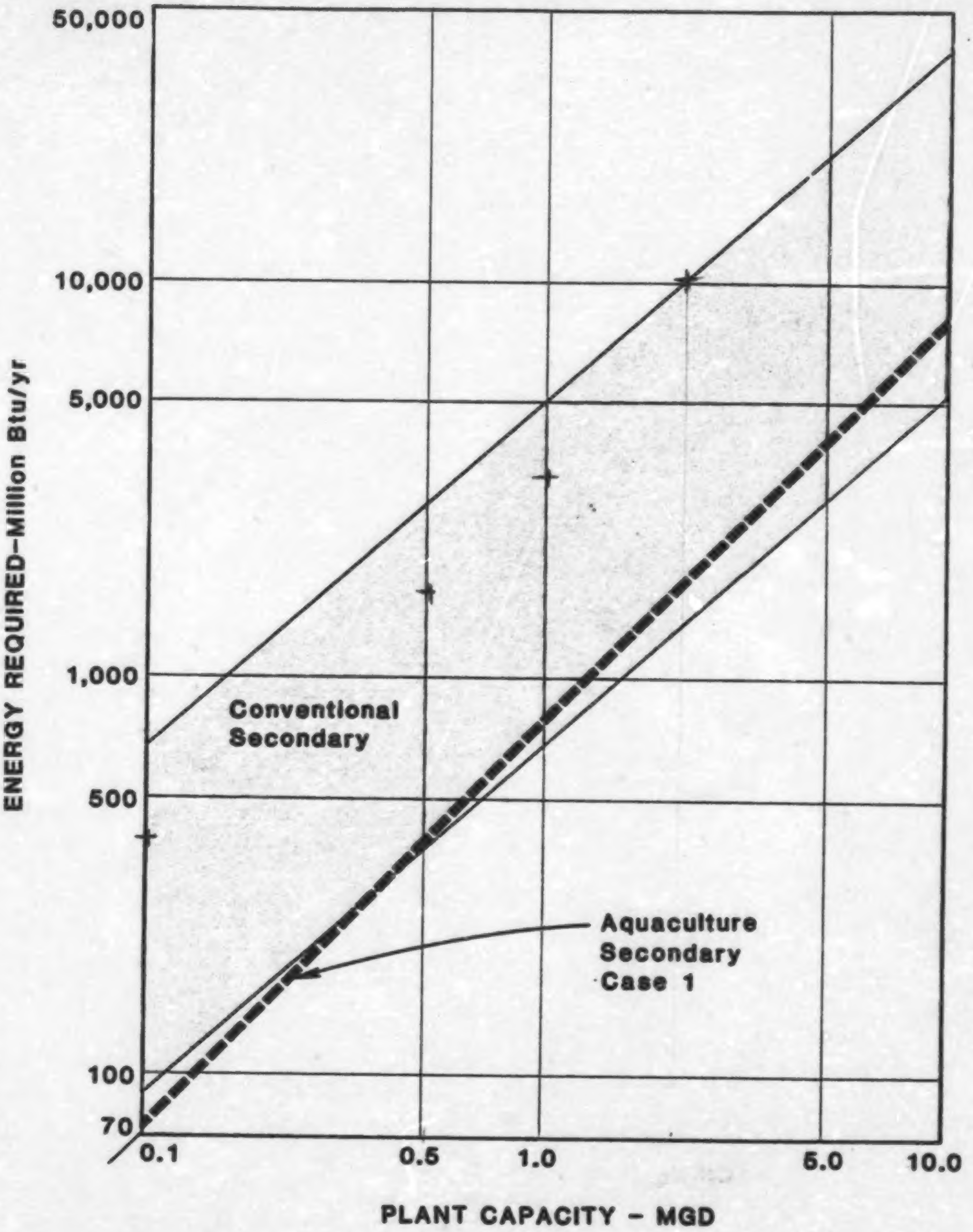


FIGURE 11. Comparison of Energy Demands – Secondary Treatment.

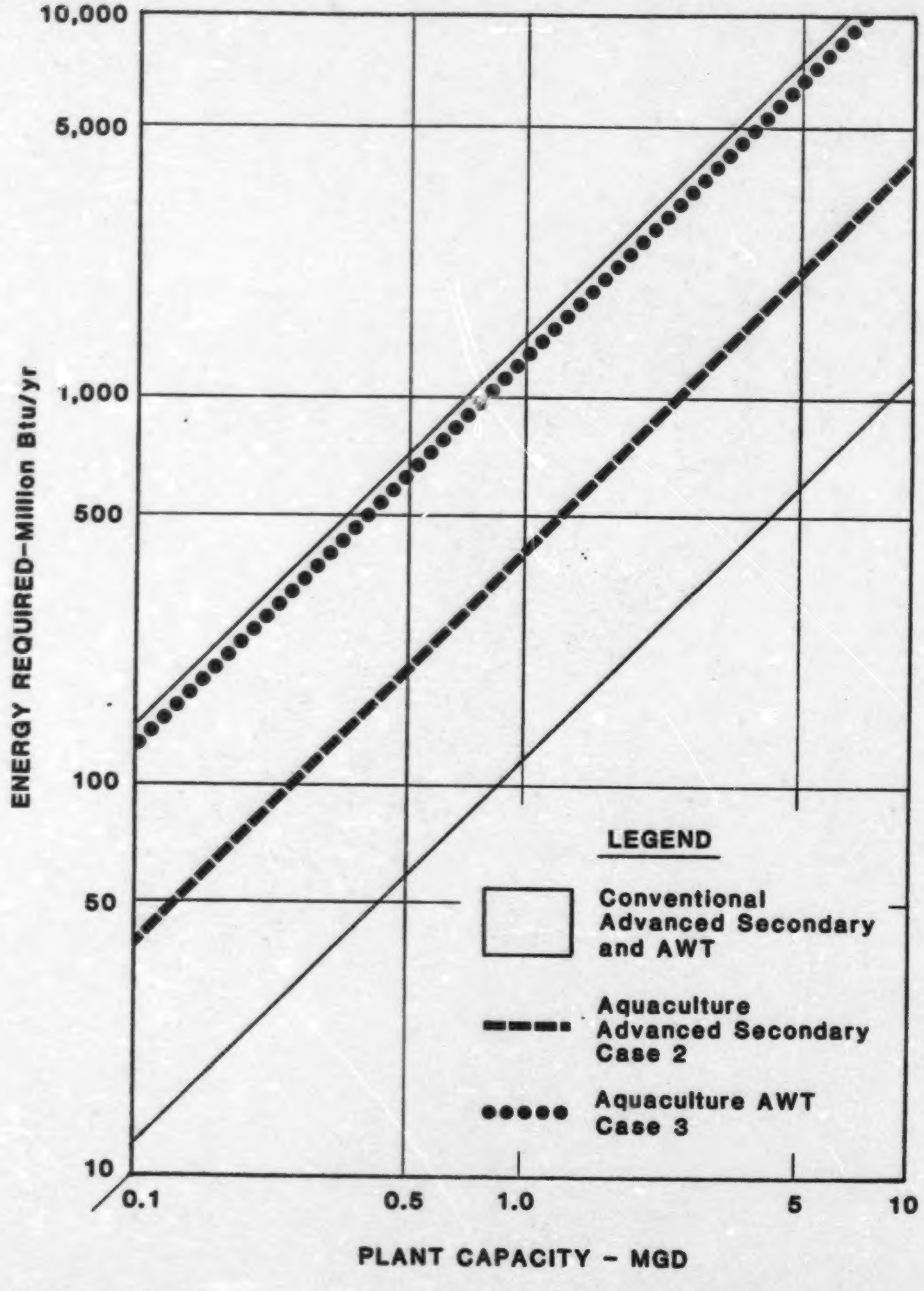


FIGURE 12. Comparison of Energy Demands – Advanced Treatment.

SECTION 6

NATIONAL IMPACT ASSESSMENT

POTENTIAL MARKET

Aquaculture systems are usually limited to suburban and rural communities because of the land area requirements. Theoretically, an aquaculture system can be designed for any capacity, but because the system is land intensive, the cost and availability of land are limiting factors for application in an urban setting.

The plants and animals that inhabit aquaculture systems are sensitive to temperature. Therefore, climate is a major factor in determining the potential market for aquaculture systems. Each of the aquaculture plant and animal species have their own optimum temperature range for growth. The temperature range given in the literature for the various species is for water temperature. Correlating the water temperature to the air temperature is a site-specific process, dependent on the size and depth of the body of water. It is difficult to determine, on a national basis, the geographical areas in which certain plants or animals would survive in a natural environment for a given period of time. However, a design manual on hyacinth systems (Reference 43) recommends a temperature range based on air temperature. It is postulated that water hyacinths would thrive in an environment where the average air temperature ranges from 4.4 to 35°C (40 to 95°F). From this guideline a rough division can be made of where an uncovered hyacinth system would be feasible. Year-round hyacinth growth in the natural environment is restricted to southern Florida and southern Texas.

An aquaculture system may also be installed for seasonal use such as for nutrient removal during the spring and summer months. Aquaculture systems may also be covered to provide a more controlled environment. However, it is likely that a system that requires the additional cost of a greenhouse structure will not be cost-effective based on the previous cost analysis. Therefore, only non-covered systems will be considered in this assessment. The potential market will be restricted to regions that have a minimum of six continuous months with a maximum average monthly temperture of 35°C (95°F) and a minimum average monthly temperature of 4.4°C (40°F).

Figure 13 locates this region on a map of the continental United States. This map is based on the temperatures reported in Reference 128.

The EPA's 1978 Needs Survey (Reference 129) estimated (for various states, flows, and treatment levels), the number of wastewater treatment plants that will be required to be constructed during the years 1978 to 2000. The temperature boundary division line (on Figure 13) crosses through the middle of some states. In tabulating the number of plants that constitute the potential market, certain assumptions were made. Where more than half of the area of a state is not included in the correct temperature zone, its number of plants were not included in the count. All plants were included for states with more than half of their boundary in the proper temperature growth zone.

Although aquaculture systems have been designed to treat raw sewage, it has been recommended that primary effluent be the minimum aquaculture influent quality. The Needs Survey gives the estimated number of secondary treatment plants, and advanced secondary and tertiary facilties that will be constructed during the years 1978 to 2000. The number of plants within the climate and capacity limitations are presented in Table 31.

TABLE 31. ESTIMATED NUMBER OF TREATMENT PLANTS TO BE CONSTRUCTED DURING THE YEARS 1978 TO 2000 WITHIN CLIMATIC ZONES FAVORABLE TO WATER HYACINTHS (Reference 129)

Level of Treatment	Total Projected Flow (m^3/day) 1-400	401-1900	1910-4000	4001-7570	Total
Secondary	2146	842	128	35	3151
Advanced	1607	595	107	115	2424
Total	3753	1437	235	150	5575

COST AND ENERGY IMPACTS

Cost

As discussed in Section 4, no monetary savings would be realized by using an aquaculture system rather than a conventional system for facilities with capacity of less than 18,900 cu m/day (5 mgd). All the aquaculture systems are expected to

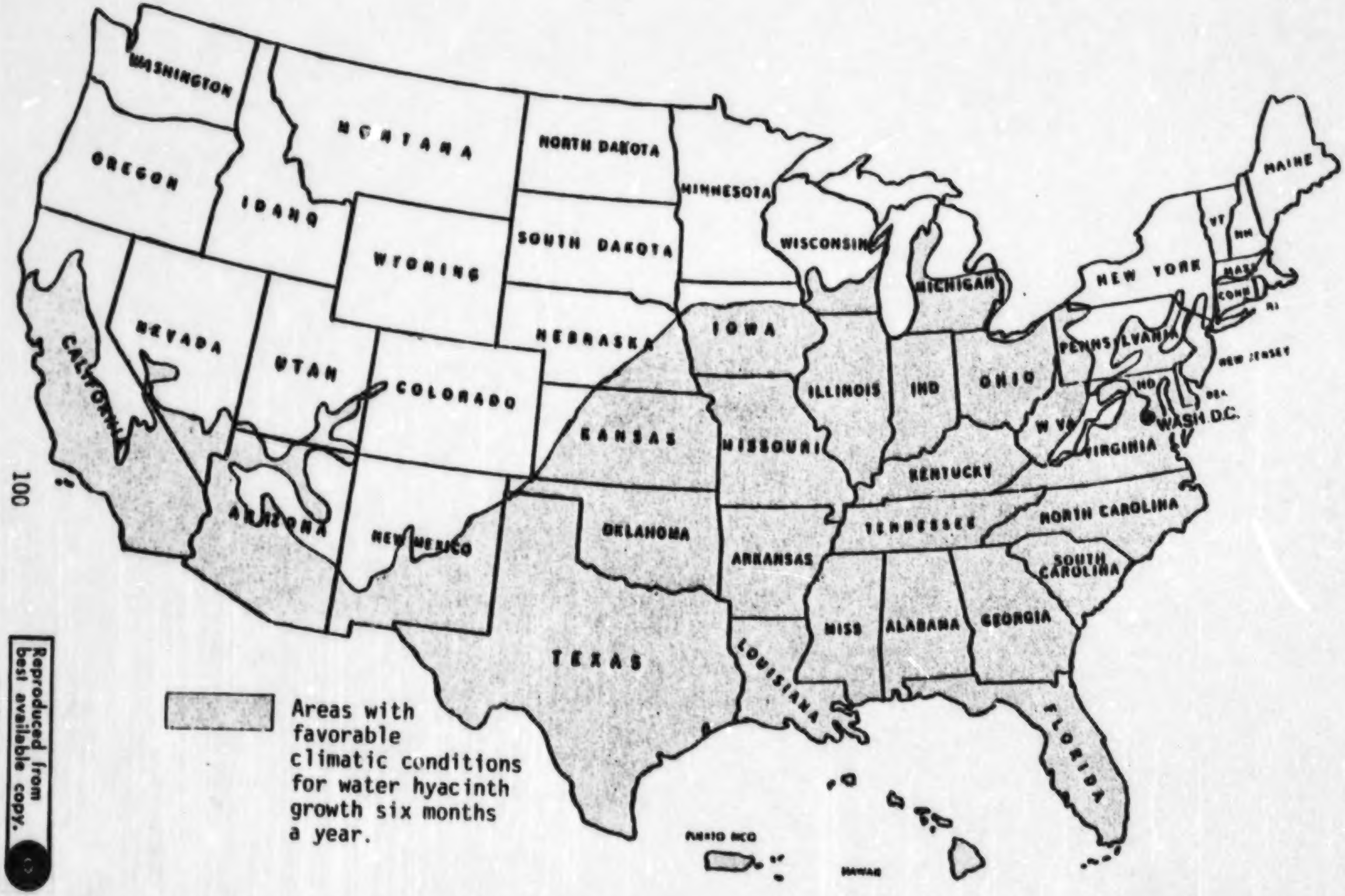

WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
MINNESOTA
WISCONSIN
MICHIGAN
NEW YORK
VT
NH
MAINE
MASS
CONN
RI
NEW JERSEY
DEL
MD
WASH D.C.
PENNSYLVANIA
OHIO
IND
ILLINOIS
IOWA
SOUTH DAKOTA
WYOMING
NEBRASKA
NEVADA
UTAH
COLORADO
CALIFORNIA
KANSAS
MISSOURI
KENTUCKY
W VA
VIRGINIA
NORTH CAROLINA
SOUTH CAROLINA
TENNESSEE
ARKANSAS
OKLAHOMA
ARIZONA
NEW MEXICO
TEXAS
LOUISIANA
MISS
ALABAMA
GEORGIA
FLORIDA
PUERTO RICO
HAWAII
Areas with favorable climatic conditions for water hyacinth growth six months a year.

FIGURE 13. Water hyacinth's approximate climatic boundary.

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be cost competitive with conventional plants, except for secondary aquaculture systems with flows greater than 5680 cu m/day (1.5 mgd). Therefore, the national impact of using advanced secondary and AWT aquaculture systems would not involve an increase or decrease in the funds expected to be spent on wastewater treatment facilities. An increase in spending is anticipated if secondary aquaculture systems with flows greater than 5680 cu m/day (1.5 mgd) were implemented. Since there are only 35 secondary treatment plants with flow greater than 5,680 cu m/day (1.5 mgd) expected to be built between 1978 and 2000 within climatic zones favorable to water hyacinths, the expected increase in spending over the next 20 years is not significant.

Energy

As discussed in Section 5, the use of aquaculture systems for secondary treatment will save energy as compared to conventional systems. However, based on the assumption used in this analysis aquaculture systems for advanced secondary and AWT could use more energy than some conventional systems.

Based on the data from the Needs Survey and the energy comparison graphs (Figure 11 and 12), Table 32 indicates the estimated energy savings. The energy demands of conventional facilities were derived from the appropriate curve on Figures 11 and 12, at the higher end of the flow range (e.g., at 400 cu m/day for the 0 to 400 cu m/day range) and at the mid-point of the cost range.

The estimated savings from the use of aquaculture systems for 10 percent of the new secondary treatment plants (under 7575 cu m/day) is 2.34×10^{11} Btu/year. The energy savings achieved by using aquaculture systems for 10 percent of advanced treatment (plants under 7575 cu m/day) is 2.86×10^{11} Btu/year.

PERSPECTIVE

Cost

The 1978 Needs Survey (Reference 129) estimates that about $14 billion would be spent over the next 20 years in the United States for secondary treatment facilities including new construction, and enlarging and upgrading existing plants. For plants with capacity less than 8,000 cu m/day the estimated cost is about $3.5 billion. The impact of the potential increase in spending from installing aquaculture systems for secondary treatment over the next 20 years should be minimal.

TABLE 32. ESTIMATED ANNUAL ENERGY DEMANDS FOR THE ANTICIPATED TREATMENT PLANTS, 1978-2000, BTU/YEAR

Level of Treatment	Total Projected Flow (cu. m./day)				
	1-400	401-1900	1910-4000	4001-7570	Total
Secondary					
Conventional					
Per plant	3.91×10^{8}	1.56×10^{9}	3.19×10^{9}	1.07×10^{10}	
10% Total US	8.54×10^{10}	1.31×10^{11}	4.15×10^{10}	4.28×10^{10}	3.01×10^{11}
Aquaculture (Case 1)					
Per plant	8.14×10^{7}	4.07×10^{8}	8.14×10^{8}	1.63×10^{9}	
10% Total US	1.75×10^{10}	3.42×10^{10}	1.06×10^{10}	6.52×10^{9}	6.75×10^{10}
Savings (Convent.-Aquaculture)	6.79×10^{10}	9.68×10^{10}	3.09×10^{10}	3.63×10^{10}	2.34×10^{11} 78%
Advanced Secondary and AWT					
Conventional					
Per plant	7.75×10^{7}	3.85×10^{8}	8.13×10^{8}	1.52×10^{9}	
10% Total US	1.25×10^{10}	2.31×10^{10}	8.94×10^{9}	1.82×10^{10}	6.27×10^{10}
Aquaculture (Case 2)					
Per plant	4.17×10^{7}	2.09×10^{8}	4.17×10^{8}	8.34×10^{8}	
10% Total US	6.71×10^{9}	1.25×10^{10}	4.59×10^{9}	1.00×10^{10}	3.38×10^{10}
Savings (Convent.-Aquaculture)	5.59×10^{9}	1.06×10^{10}	4.35×10^{9}	8.20×10^{9}	2.86×10^{10} 46%

For advanced secondary treatment and AWT facilities (including new construction, and enlarging and upgrading existing plants), the Needs Survey estimates that $20 billion will be spent over the next 20 years. For plants with flows less than 8,000 cu m/day, the estimate is about $4.9 billion. Since the cost of advanced systems is comparable with conventional systems, there should not be any impact on the amount of funds required for advanced treatment of plants with flows less than 8,000 cu m/day.

Energy

As reported in the EPA publication Energy Conservation in Municipal Wastewater Treatment (Reference 130), the 1990 estimated energy consumption at publicly owned treatment works for secondary treatment is 216.51×10^{12} Btu/year and 40.40×10^{12} Btu/year for tertiary treatment. The 1990 national energy use is estimated to be 1145×10^{15} Btu/year. The savings realized by using aquaculture systems for secondary and advanced treatment systems are insignificant when compared to the national energy budget.

MARKETABILITY

As previously discussed, the potential market for aquaculture systems is limited in relation to the market for all wastewater treatment facilities in the United States. This market is generally limited to suburban and rural communities that have large areas of reasonably priced land available and wastewater flows less than 8,000 cu m/day.

The marketability of aquaculture requires that a community select an aquaculture system over another system. However, a certain level of risk is associated with the selection of an aquaculture system. The risks are due to aquaculture systems being an unproven wastewater treatment technology, and because they are natural systems dependent on environmental conditions. The risk is reduced with each aquaculture system implemented. As more performance data are developed, the more refined and reliable the design criteria become. Natural systems have the added drawback that direct control over the process is limited.

A community may justify the risk of selecting aquaculture systems by arguing that the risks involved with conventional plants are similar. Many existing conventional treatment systems have not met effluent discharge requirements and are experiencing operational problems.

The risks involved with aquaculture systems vary. There are two possible results in situations where aquaculture systems are installed and fail to perform. First, the aquaculture system may be abandoned and a new treatment system installed. In this case about 3 to 7 percent of the capital cost may be regained by selling the land. Salvaging equipment and materials may also reduce the losses. About 28 to 45 percent of the capital cost is for earthwork, which cannot be reclaimed and would have to be taken as a direct loss. The second possible result is that the new treatment process may incorporate the aquaculture system into its design.

SECTION 7

LIST OF REFERENCES AND CONTACTS

1. Bardach, J.E., J.H. Ryther, and W.O. McLarney, 1972. Aquaculture, Wiley & Sons, New York, 868 p.

2. Duffer, W.R. and C.C. Harlin, Jr., 1979. "Potential of Aquaculture for Reclamation of Municipal Wastewater," in Proceedings - Water Reuse Symposium, Vol. 1, American Water Works Association Research Foundation, Denver, Colorado, pp 740-46.

3. United States Environmental Protection Agency MERL, 1982. Emerging Technology Assessment of Wetlands Wastewater Treatment Systems.

4. Allen, G.H., 1969. A Preliminary Bibliography on the Utilization of Sewage in Fish Culture. FAO Fish. Circ., (308):15 p.

5. Allen, G.H., 1972. "The Constructive Use of Sewage, with Particular Reference to Fish Culture," in Marine Pollution and Sea Life, M. Ruivo (ed.), West Byfleet, Surrey, Fishing News (Books), pp. 506-13.

6. Carpenter, R.L. (ed.), 1974. Wastewater Use in the Production of Food and Fiber, Proceedings of Conference, Oklahoma City, March 5 - 7, 1974. Environ. Protect. Tech. Ser., Wash., D.C. (EPA-660/2-74-041) 568 p.

7. Pillay, T.V.R. and W.A. Dill (Eds.), 1977. Advances in Aquaculture, papers presented at the FAO Technical Conference on Aquaculture, Kyoto, Japan, 26 May - 2 June, 1976. Fishing News Books Ltd, England, 651 p.

8. Tourbier, J. and R.W. Pierson, Jr., (Eds.), 1976. Biological Control of Water Pollution, University of Pennsylvania Press, Philadelphia, Penn., 335 p.

9. D'Itri, F. (Ed.), 1977. Wastewater Renovation and Reuse, Marcel Dekker, Inc., New York and Basel, 705 p.

10. Duffer, W.R. and J.E. Moyer, 1978. Municipal Wastewater Aquaculture, U.S. Environmental Protection Agency (EPA-600/2-78-110), R.S. Kerr Environmental Research Laboratory, Ada, Oklahoma, 47 p.

11. Bastian, R.K. and S.C. Reed (Eds.), 1979. Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, University of California Davis, September 11-12, 1979. U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-006, MCD-67), 485 p.

12. S.C. Reed and Bastian R.K. (Eds.), 1980. Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-007, MCD-68), 127 p.

13. Stowell, R., R. Ludwig, I. Colt, and G. Tchobanoglous, 1980. Toward the Rational Design of Aquatic Treatment Systems, Presented at the American Society of Civil Engineers Spring Convention, Portland, Oregon, April 14-18, 1980, 58 p.

14. Reed, S., R. Bastian, and W. Jewell, 1980. "Engineering Assessment of Aquaculture Systems for Wastewater Treatment: An Overview", in Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-007, MCD-68), pp 1-12.

15. Schwartz, Jr., H.G., and B.S. Skin, 1980. "Combined Aquaculture Systems for Municipal Wastewater Treatment", in Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-007, MCD-68), pp 81-104.

16. Middlebrooks, J.E., 1980. "Aquatic Plant Processes Assessment", in Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, (EPA 430/9-80-007, MCD-68), U.S. Environmental Protection Agency, Wash., D.C., pp 43-62.

17. Ludwig, R. et al. 1980. The Use and Potential of Aquatic Species for Wastewater Treatment, Appendix E, The Use of Aquatic Systems for Wastewater Treatment: An Assessment, Publication No. 65, California State Water Resources Control Board, Sacramento, California.

18. Stephenson, M., G. Turner, P. Pope, A. Knight, and G. Tchobanoglous, 1980. The Use and Potential of Aquatic Species for Wastewater Treatment, Appendix A, The Environmental Requirements of Aquatic Plants. Publication No. 65, California State Water Resources Control Board, Sacramento, CA., 380 pp.

19. Colt, J., S. Mitchell, G. Tchobanoglous, and A. Knight, 1979. The Use and Potential of Aquatic Species for Wastewater Treatment, Appendix B, The Environmental Requirements of Fish, Publication No. 65, California State Water Resources Control Board, Sacramento, California, 240 pp.

20. Colt, J., S. Mitchell, G. Tchobanoglous, and A. Knight, 1980. The Use and Potential of Aquatic Species for Wastewater Treatment, Appendix C, The Environmental Requirements of Crustaceans, Publication No. 65, California State Water Resources Control Board, Sacramento, California.

21. Colt, J., S. Mitchell, G. Tchobanoglous, and A. Knight, 1980. The Use and Potential of Aquatic Species for Wastewater Treatment, Appendix D. The Environmental Requirements of Freshwater Bivalves, Publication No. 65, California State Water Resources Control Board, Sacramento, California.

22. Wolverton, D.C. and R.C. McDonald, 1978. Compiled Data on the Vascular Aquatic Plant Program: 1975-77, NASA National Space Technology Laboratories, Bay St. Louis, Mississippi, 148 p.

23. Boyd, C.E., 1970. "Vascular Aquatic Plants for Mineral Nutrient Removal from Polluted Waters," Economic Botany 24:95-103.

24. Hillman, W.S. and D.D. Culley, Jr., 1978. "The Uses of Duckweed," American Scientist 66:442-451.

25. Penfound, W.T., and T.T. Earle, 1948. "The Biology of the Water Hyacinth," Ecological Monographs 18 (4):447-472.

26. Pieterse, A.H., 1975. The Water Hyacinth (Eichhornia crassipes) - A Review, Department of Agricultural Research, Boyal Tropical Institute, Amsterdam, 42 p.

27. Robinson, A.C., et al. 1976. An Analysis of the Market Potential of Water Hyacinth Based Systems for Municipal Wastewater Treatment, Report No. BCL-OA-

TFR-76-5, Battelle Columbus Laboratories, Columbus, Ohio, 235 p.

28. Hannah, R.P., and L.K. Clark, 1976. Saltwater Tolerance of the Water Hyacinth, Eichhornia crassipes, NASA National Space Technology Laboratories, Bay St. Louis, Mississippi, 15 p.

29. O'Brien, W. J. 1980. "Engineering Assessment: Use of Aquatic Plant Systems for Wastewater Treatment," in Aquatic Systems for Wastewater Treatment: An Engineering Assessment, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-007, MCD-68), pp 63-80.

30. Westlake, D.F., 1963. "Comparisons of Plant Productivity," Biological Review, 38:385-425.

31. Wooten, J.W., and J.C. Dodd, 1976. "Growth of Water Hyacinth in Treated Sewage Effluent," Economic Botany 30 (1):29-37.

32. Wolverton, B.C., and R.C. McDonald, 1978. "Nutritional Composition of Water Hyacinths Grown on Domestic Sewage," Economic Botany 32 (4):363-370.

33. Ryther, J.H. et al. No date. Freshwater Macrophytes for Energy and Wastewater Treatment, Contribution No. 4312, Woods Hole Oceanographic Institute, Woods Hole, Mass., 17 p.

34. Cornwell, D.A., 1977. "Nutrient Removal by Water Hyacinths," J. Water Pollution Control Federation 49 (1):57-65.

35. Wolverton, B.C., and R.C. McDonald, 1978. "Water Hyacinth Productivity and Harvesting Studies," Economic Botany 33 (1):1-10.

36. Harvey, R.M. and J.L. Fox, 1973. "Nutrient Removal Using Lemna minor," J. Water Pollution Control Federation 45:1928-1938.

37. Culley, J.J., and E.A. Epps, 1973. "Use of Duckweed for Waste Treatment and Animal Feed," J. Water Pollution Control Federation 45 (2):337-347.

38. Lin, S.Y., 1974. "The Dialectics of a Proposal on Biological Control of Eutrophication in Sewage Lagoons," in Wastewater Use in the Production of Food

and Fiber-Proceedings, Environmental Protection Tech. Ser. Wash., D.C. (EPA-660/2-74-041), pp 417-34.

39. Henderson, S., 1979. "Utilization of Silver and Bighead Carp for Water Quality Improvement," in Aquaculture Systems for Wastewater Treatment: Seminar Procedures, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-006, MCD-67), pp 309-350.

40. Coleman, M.S., et al. 1974. "Aquaculture as a Means to Achieve Effluent Standards," in Wastewater Use in the Production of Food and Fiber-Proceedings, Environ. Protect. Tech. Ser., Wash., D.C. (EPA-660/2-74-041), pp 199-214.

41. Dinges, R., 1979. "Development of Hyacinth Wastewater Treatment Systems in Texas," in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-006, MCD-67), pp. 193-232.

42. Wolverton, B.C., 1979. "Engineering Design Data for Small Vascular Aquatic Plant Wastewater Treatment Systems," in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, U.S. Environmental Protection Agency, Wash., D.C. (EPA 430/9-80-006, MCD-67) pp. 179-192.

43. Gee & Johnson Engineers, 1980. Water Hyacinth Wastewater Treatment Design Manual for NASA/National Space Tech. Lab., West Palm Beach, Fla., 92 p.

44. Steward, K.K., 1970. "Nutrient Removal Potentials of Various Aquatic Plants," Hyacinth Control Journal 8:34-35.

45. Rodgers, H.H., and D.E. Davies, 1972. "Nutrient Removal by Water Hyacinth," Weed Science 20 (5):423-428.

46. Ornes, W.T. and D.L. Sutton, 1975. "Removal of Phosphorus from Static Effluent by Water Hyacinth," Hyacinth Control Journal 13:56-58.

47. Sheffield, C.W., 1967. "Water Hyacinth for Nutrient Removal," Hyacinth Control Journal 6:27-30.

48. Scarsbrook, E., and D.E. Davis, 1971. "Effect of Sewage Effluent on the Growth of Five Vascular Aquatic Species," Hyacinth Control Journal 9:26-30.

49. Wolverton, B.C., and R.C. McDonald, 1975. *Water Hyacinths and Alligator Weeds for Final Filtration of Sewage*, NASA Technical Memorandum, TMX-72724, National Space Technology Laboratories, Bay St. Louis, Mississippi, 7 p.

50. Wolverton, B.C., R.M. Barlow, and R.C. McDonald, 1976. "Application of Vascular Aquatic Plants for Pollution Removal, Energy, and Food Production in a Biological System," *Biological Control of Water Pollution*, J. Tourbier and R.W. Pierson (Eds.) Philadelphia, PA, University of Pennsylvania, pp. 141-149.

51. Wolverton, B.C. and R.C. McDonald, 1975. *Water Hyacinths and Alligator Weeds for Removal of Lead and Mercury from Polluted Waters*, NASA Tech. Memorandum X-72723, National Space Technology Laboratories, Bay St. Louis, Mississippi, 12 p.

52. Wolverton, B.C., 1975. *Water Hyacinths for Removal of Cadmium and Nickel from Polluted Waters*, NASA Technical Memorandum X-72721, National Space Technology Laboratories, Bay St. Louis, Mississippi, 8 p.

53. Wolverton, B.C., and R.C. McDonald, 1975. *Water Hyacinths and Alligator Weeds for Removal of Silver, Cobalt, and Strongium from Polluted Waters*, NASA Technical Memorandum X-72727, National Space Technology Laboratories, Bay St. Louis, Mississippi, 11 p.

54. Sutton, D.L., and R.D. Blackburn, 1971. "Uptake of Copper by Water Hyacinth," *Hyacinth Control Journal* 9:18-20.

55. Wolverton, B.C. and M.M. McKown, 1976. "Water Hyacinths for Removal of Phenols from Polluted Waters," *Aquatic Botany* 2:191-201.

56. Harvey, R.M., and J.L. Fox, 1973. "Nutrient Removal Using *Lemna minor*," *J. Water Pollution Control Fed*. 45:1928-1838.

57. Sutton, D.L., and W.H. Ornes, 1975. "Phosphorus Removal from Static Sewage Effluent Using Duckweed," *J. Environmental Quality* 4 (3):367-370.

58. Sutton, D.L., and W.H. Ornes, 1977. "Growth of *Spirodela polyrhiza* in Statis Sewage Effluent," *Aquatic Botany* 3 (3):231-237.

59. Furman,. T. des. and F.W. Gilcreas, 1965. *The Application of Oxidation Ponds to Treatment of Residential Wastes*, Unpublished Report, Phelps Laboratory, University of Florida.

60. Clock, R.M., 1968. *Nitrogen and Phosphate Removal from a Secondary Sewage Treatment Effluent*, Doctorial Disseratation, University of Florida, Gainsville, Florida.

61. Sheffield, C.W., and T. des. Furman, 1969. *Biological and Chemical Means of Removing Nutrients*, presented at 42nd Annual WPCA Conference, Dallas, Texas.

62. Minor, R.J., J.W. Wooten, and J.D. Dodd, 1971. "Water Hyacinths to Further Treat Anaerobic Lagoon Effluent," *Livestock Waste Management and Pollution Abatement*, American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 170-173.

63. Neuse, D.W., 1976. *The Removal of Algae from Oxidation Pond Effluent through the Use of a Tertiary Water Hyacinth Pond System*, Master Thesis, University of Texas, Austin, Texas.

64. Cornwell, D.A., J. Zoltek, Jr, C.D. Patrinely, T. deS. Furman, and J.I. Kim, 1977. "Nutrient Removal by Water Hyacinths," *J. Water Pollution Control Federation* 49 (1):57-65.

65. Dinges, R., 1978. "Upgrading Stabilization Pond Effluent by Water Hyacinth Culture," *J. Water Pollution Control Federation* 50 (5):833-845.

66. Dinges, W.R., 1976. "Who Says Sewage Treatment Plants Have to be Ugly?" *Water and Wastes Engineering* 13:29-23.

67. Wolverton, B.C., 1980. *Higher Plants for Recycling Human Waste into Food, Potable Water and Revitalized Air in a Closed Life Support System*. NASA/ERL Report No. 192, National Space Technology Laboratories, Bay St. Louis, Mississippi, 30 p.

68. Wolverton, B.C., and Rebecca McDonald, 1979. "Upgrading Faculative Waste Lagoons with Vascular Aquatic Plants," *Journal Water Pollution Control Federation* 51 (2):305-313.

69. McDonald, R.C., 1979. "A Comparative Study of a Domestic Wastewater Lagoon With and Without Water Hyacinths," Economic Botany 34 (2):101-110.

70. King, D.L., and T.M. Burton, 1979. "A Combination of Aquatic and Terrestrial Ecosystems for Maximal Reuse of Domestic Wastewater," in Water Reuse Symposium-Proceedings (Vol. 1), American Water Works Association. Research Foundation, Denver, Colorado, pp 714-726.

71. McNabb, C.D., 1976. "The Potential of Submersed Vascular Plants for Reclamation of Wastewater in Temperate Zone Ponds," in Biological Control of Pollution, J. Tourbier and R.W. Pierson, Jr., (Eds.), University of Pennsylvania, Philadelphia, PA, pp.123-132.

72. Swett, D., 1979. "A Water Hyacinth Advanced Wastewater Treatment System," Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, (EPA 430/9-80-006 MCD-67), pp.233-256.

73. Stewart, E.A., 1979. "Utilization of Water Hyacinths for Control of Nutrients in Domestic Wastewater - Lakeland, Florida," in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, (EPA 430/9-80-006, MCD-67), pp. 273-293.

74. Kruziac, A.P., 1979. "Water Hyacinth Wastewater Treatment System at Disney World," in Aquaculture Systems for Wastewter Treatment: Seminar Proceedings, (EPA 430/9-80-006, MCD-67), pp. 257-272.

75. WED Enterprises, 1980. Water Hyacinth Wastewater Treatment System at Walt Disney World, Florida - Final Report for the Period August 1978 - April 1980, Unpublished Report, Glendale, CA 47 pp.

76. Serfling, S.A., and D. Mendola, 1979. "The Solar Aquacell AWT Lagoon System for the City of Hercules, California," in Proceedings - Water Reuse Symposium, (Vol. 1), American Water Works Association Research Foundation, Denver, Colorado, pp. 671-680.

77. Stewart, W.C. and S.A. Serfling, 1979. "The Solar Aquacell AWT Lagoon System for Primary, Secondary, or Advanced Treatment of Wastewaters," in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, (EPA 430/9-80-006, MCD-67), pp. 377-414.

78. McShan, M., N.M. Trieff, and D. Grajcer, 1974. "Biological Treatment of Wastewater Using Algae and *Artemia*," *J. Water Pollution Control Federation* 46 (7):1742-1750.

79. Trieff, N.M. et al. 1976. "Sewage Treatment by Controlled Eutrophication Using Algae and *Artemia*," in *Biological Control of Water Pollution*, J. Tourbier and R.W. Pierson (Eds.) Universtiy of Pennsylvania, Philadelphia, Penn., pp. 231-239.

80. Dinges, R., 1974. "The Availability of *Daphnia* for Water Quality Improvement and as an Animal Food Source," in *Wastewater Use in the Production of Food and Fiber*, Environ. Protect. Tech. Ser., Wash, D.C., (EPA-660-2-74-041), pp. 142-161.

81. Dinges, R., 1976. "A Proposed Integrated Biological Wastewater Treatment System," in *Biological Control of Water Pollution*, J. Tourbier and R.W. Pierson, Jr. (Eds.), University of Pennsylvania, Philadelphia, Penn., pp 225-230.

82. Dinges, R., 1975. "Wee Beasties May Improve Your Effluent," *Water and Wastes Engineering* 12:35-37.

83. Las Virgenes Municipal Water District, 1973. *Tertiary Treatment with a Controlled Ecological System*, U.S. Environmental Protection Agency, (EPA-660-2-73-022).

84. Tsai, Chu-Fa, 1975. *Effects of Sewage Treatment Plant Effluents on Fish: A Literature Review*. Chesapeake Res. Consortium Pub. No. 36, Univ. Maryland, MD., pp. 220-229.

85. Huggins, T.G. and R.W. Bachmann, 1969. *Production of Channel Catfish (Ictaluvus punctatus) in Tertiary Treatment Ponds*, Iowa State Resources Research Inst. Ames, Iowa, 112 p.

86. Konefes, J.L., and R.W. Bachmann, 1970. "Growth of the Fathead Minnow (*Pimephales promelas*) in Tertiary Treatment Ponds," *Iowa Academy of Science* 77:104-111.

87. Trimberger, J., 1972. *Production of Fathead Minnows (Pimephalas promelas) in a Municipal Wastewater System*, Michigan Dept. of Natural Resources, Fisheries Div., 5 pp.

88. Ave Lallemant, S.P., and J.W. Held, 1980. *Assessment of Sewage Lagoons as Potential Fish Culture Sites in*

West Central Wisconsin, Technical Report WIS-WRC 80-10, University of Wisconsin Water Resources Center, Madison, Wisconsin, 83 p.

89. Hallock, R.J., and C.D. Ziebell, 1970. "Feasibility of a Sport Fishery in Tertiary Treated Wastewter," J. Water Pollution Control Federation 42 (9):1656-65.

90. Anon. 1979. "Little Fish Big Help in Sewage Treatment", Farm Pond Harvest 13 (1):8-9.

91. Carpenter, R.L., M.S. Coleman, and R. Jarmon, 1976. "Aquaculture as an Alternative Wastewater Treatment System," in Biological Control of Pollution, J. Tourbier and R.W. Pierson, Jr., (Eds.) University of Pennsylvania, Philadelphia, Penn., pp. 215-24.

92. Hepher, B. and G. Schroeder, 1977. "Wastewater Utilization Israel Aquaculture", in Wastewater Renovation and Reuse, F. D'Itri (Ed.) Marcel Dekker, Inc., New York and Basel, pp. 529-59.

93. Buck, D.H., 1977. "The Integration of Aquaculture with Agriculture," Fisheries 2 (6):11-16.

94. Ryther, J.H., J.L. Goldmen, C.E. Gifford, and J.E. Hygyenin, 1975. "Physical Models of Integrated Waste Recycling-Marine Polycultured Systems," Aquaculture 5:163-177.

95. Goldman, J.C., and J.H. Ryther, 1976. "Waste Reclamation in an Integrated Food Chain System," in Biological Control of Water Pollution J. Tourbier and R.W. Pierson, Jr., (Eds.), University of Pennsylvania Press, Philadelphia, Penn. pp. 197-214.

96. Ryther, J.H., 1977. "Preliminary Results with a Pilot-Plant Waste Recycling-Marine Aquaculture System," in Wastewater Removation and Reuse, F. D'Itri (Ed.), Marcel Dekker, Inc. New York and Basel, pp. 89-132.

97. Ryther, J.H., 1979. "Treated Sewage Effluent as a Nutrient Source for Marine Polyculture" in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, (EPA 430/9-80-006, MCD-67), pp 351-376.

98. Mann, R. and J.H. Ryther, 1977. "Growth of Six Species of Bivalve Mollusks in a Waste-Recycling Aquaculture System," in Aquaculture 11:231-45.

99. Mann, R., 1978. "Growth of Mytilusedulis in a Waste-Recycling Aquaculture System," Aquaculture 13:351-54.

100. Mann, R. and J.H. Ryther, 1979. "Trace Contaminant Accumulation by Organisms Grown in a Waste Recycling Aquaculture System," in Proc. World Mariculture Society 10:809-22.

101. Moss, M., 1979. "Obtaining Water: San Diego's Non-Traditional Approach," Western City (June):13-14.

102. Bagnell, L.L., R.L. Shirley, and F. Hentges, 1973. Processing, Chemical Composition and Nutritive Value of Aquatic Weeds, Florida Water Resources Research Center, Publication No. 25, University of Florida, Gainesville, Florida, 55 pp.

103. Bagnell, L.O., 1979. "Resource Recovery from Wastewater Aquaculture," in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, (EPA 430/9-80-006, MCD-67), US EPA, pp. 421-440.

104. King, R.W., 1979. "Recycle and San Diego," in Proceedings - Water Reuse Symposium, (Vol. 1), American Water Works Association Research Foundation, Denver, Colorado, pp. 681-684.

105. Schroeder, G.L., 1975. "Some Effects of Stocking Fish in Waste Treatment Ponds", Water Research 9:591-593.

106. Oswald, W., 1972. "Complete Waste Treatment In Ponds", Sixth International Water Pollution Research B/3/61, Pergamon Press, Oxford.

107. Timmer, C.E. and L.W. Weldon, 1967. "Evapotranspiration and Pollution of Water by Water Hyacinth", Hyacinth Control Journal 6:34.

108. Idso, S.B., 1979. "Discussion: Evapotranspiration from Water Hyacinth (Eichhornia crassipes) in Texas Reservoirs," Water Resources Bulletin 15:1466.

109. Persche, E.R., 1980. "Combined Aquaculture Systems for Wastewater Treatment in Cold Climates - An Engineering Assessment", in Aquaculture Systems for Wastewater Treatment: An Engineering Assessment, U.S. Environmental Protection Agency (EPA 430/9-80-007, MCD-68), pp. 105-127.

110. Allen, G.H. and B. Hepher, 1977. "Recycling of Wastes Through Aquaculture, and Constraints to Wider

Application", in Advances in Aquaculture, Pillay, T.V.R. and W.A. Dill (Eds.), Fishing News Books, England, pp. 478-486.

111. Shewal, H.I., 1977. "Public Health Implications of Wastewater Reuse for Municipal Purposes", in Wastewater Renovation and Reuse, F.D'Intri (ed.), Marcel Dekker Inc., New York and Basel, pp.349-386.

112. Bryan, F.L., 1974. "Diseases Transmitted by Foods Contaminated by Wastewater", in Wastewater Use in the Production of Food and Fiber-Proceedings, Environ. Prot. Tech. Series, (EPA-660/2-74-041), pp. 16-45.

113. McGarry, M.G., 1977. "Domestic Wastes as an Economic Resource: Biogas and Fish Culture", in Water, Wastes, and Health in Hot Climates, R. Feachern et al. (eds.), Wiley Interscience, John Wiley and Sons, London.

114. Kerfoot, W.B. and S.A. Jacobs, 1974. "Permissible Levels of Heavy Metals in Secondary Effluents for Use in a Combined Sewage Treatment-Marine Aquaculture System I. Monitoring during Pilot Operation", in Wastewater Use in the Production of Food and Fiber-Proc., Environ. Prot. Tech. Series (EPA-660/2-74-041), pp.65-78.

115. Kerfoot, W.B. and G.A. Redmann, 1974. "Permissible Levels of Heavy Metals in Secondary Effluents for Use in a Combined Sewage Treatment-Marine Aquaculture System II. Development of Guidelines by Methods of Additons", in Wastewater Use in Protection of Food and Fiber-Proc., Environ. Prot. Tech. Series (EPA-660/2-74-041) pp. 79-101.

116. Huguenin, J.E. and J.T. Kildow, 1974. "Social, Political, Regulatory and Marketing Problems of Marine Waste-Food Recycling Systems", in Wastewater Use in the Production of Food and Fiber-Proc., Environ. Prot. Tech. Series (EPA-660/2-74-041), pp. 344-356.

117. D'Itri, F.M. and P.A. D'Itri, 1977. "Public Attitudes Toward Renovation and Reuse of Municipal Wastewater", in Wastewater Renovation and Reuse, F.D'Itri (ed.), Marcel Dekker Inc., New York and Basel, pp. 603-642.

118. Huguenin, J.E. and J.D. Little, 1977. "Marketing Issues of 'Waste' Grown Aquatic Foods", Environmental Management, 1 (5):433-440.

119. Lohman, L.C., 1979. "An Overview of the Legal, Political, and Social Implications of Wastewater Treatment through Aquaculture", in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, U.S. Environmental Protection Agency, Washington, D.C. (EPA-430/9-80-006 , MCD-67) pp.459-472.

120. Ryther, J.H. W.M. Dustan, K.R. Tenore, and J.E. Hygyenin, 1972. "Controlled Eutrophication-Increasing Food Production from the the Sea by Recycling Human Wastes", Bioscience 22:144-152.

121. Tchobanogous, G., R. Stowell, R. Ludwig, J. Colt, and A. Knight, 1979. "The Use of Aquatic Plants and Animals for the Treatment of Wastewater: An Overview", in Aquaculture Systems for Wastewater Treatment: Seminar Proceedings, U.S. Environmental Protection Agency (EPA-430/9-80-006, MCD-67) pp.35-55.

122. Metcalf and Eddy, Inc., 1972. Wastewater Engineering, McGraw Hill, New York.

123. Crites, Ronald, 1979. "Economics of Aquatic Treatment Systems" in Aquaculture Systems for Wastewater Treatment: Seminar Proceeding, U.S. Environmental Protection Agency (EPA 430/9-80-006, MCD-67), pp 475-485.

124. Culp, Wesner, Culp, 1977. Process Design, Performance and Economic Analysis Handbook, Biological Wastewater Treatment Process, for Wastewater Treatment and Reuse Seminar, South Lake Tahoe, CA.

125. United States Environmental Protection Agency, 1980. Innovative and Alternative Technology Assessment Manual, (EPA 430/9-78-009, MCD-53) February.

126. Tchobanoglous, G., J. Colt, and R. Crites, 1979. "Energy and Resource Consumption in Land and Aquatic Treatment Systems", prepared for the Energy Optimization of Water & Wastewater Management for Municipal and Industrial Applications Conference, Department of Energy, New Orleans, Louisiana, December 10-13, 1979, 12 pp.

127. Roberts, Edwin and Robert Magan, 1977. Guidelines for the Estimation of Total Energy Requirement of Municipal Wastewater Treatment Alternatives. A report to the State Water Resources Control Board, California by the University of California at Davis, August 1977.

128. U.S. Department of Commerce, 1968. Weather Atlas of the United States, Reprinted 1975 by Gale Research Company, Detroit, Michigan.

129. United States Environmental Protection Agency, 1979. 1978 Needs Survey, Conveyance and Treatment of Municipal Wastewater, Summaries of Technical Data, FRD-2, February 1979.

130. Wesner, George, G.L. Culp, T.S. Lineck, and D.J. Hinrichs, 1978. Energy Conservation in Municipal Wastewater Treatment, (EPA 430 9-7-011, MCD-32), March 1978.

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